Use of Material in Residential House Design: An Optimisation Approach Balancing Life Cycle Cost & Life Cycle Environmental Impact

Hamidul Islam

Doctor of Philosophy

2012

RMIT University

Use of Material in Residential House Design: An Optimisation Approach Balancing Life Cycle Cost & Life Cycle Environmental Impact

A thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

Hamidul Islam

B.Sc. (Forestry) Hons, M.Sc. (Environmental Management)

School of Civil, Environmental and Chemical Engineering

RMIT University, Melbourne, Australia

September 2012

DECLARATION

I, Hamidul Islam, declare that the PhD thesis entitled 'Use of Material in Residential House Design: An Optimisation Approach Balancing Life Cycle Cost & Life Cycle Environmental Impact' is no more than 100,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography and footnotes.

This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work.

Signature....................

Hamidul Islam

September 2012

ABSTRACT

There is a broad consensus that environmental impact of buildings is reduced through use of more environmentally friendly materials in conjunction with conventional insulating materials, careful design, assembly, and climate. However, there is no certainty that use of such materials ensures a positive impact on the environment unless a whole life cycle perspective is taken.

Popular house designs in Australia include brick, concrete, timber and timber composites. Insulating materials are used to improve the building envelope thermal performance. Stakeholders generally select the “best” design after considering only star rating and construction costs. However, what is the certainty that this is the optimum design, from both an environmental and cost perspective? Is the optimum design the same if a narrow or wide range of building materials and assemblage designs is considered? If a narrow or wide range of environmental and economic impact indicators is considered, what is the value for stakeholders? What is the most useful optimisation model to identity the best designs?

In this study, a sample recently built Brisbane house was adopted as a case study. Its envelope components were varied to achieve different star ratings. Materials (wall claddings, rooftops and floor tops) and assemblage dimensions (insulation and air gap thickness, roof inclination) were selected based on their importance and relative effectiveness in achieving a particular star rating. The environmental and cost impacts were assessed across a 50-year life cycle. The Bill of Quantity (BOQ) was calculated for each alternative design, and then the annual operational energy requirements were modelled using *AccuRate* software. These data were then used to build a life cycle assessment (LCA) model using *SimaPro* software. Life cycle costs (LCC) were calculated using the BOQ and industry standard prices to find the present value of the house using suitable inflation and discount rates. Finally, various optimisation models were trialled to assess their usefulness in identifying the best design, one where life cycle cost and environmental impacts were balanced subject to sets of constraints. Various sets of constraints were evaluated.

The impacts of material selection and assemblage design on selected environmental and economic indicators were assessed across the life cycle stages of construction, operation, maintenance and disposal. Four environmental impacts category indicators were selected including greenhouse gas (GHG) emission, cumulative energy demand (CED), water usage and solid waste. One economic indicator was selected, life cycle costs including present value of future costs.

The results show that GHG, solid waste and LCC are significantly affected by wall assemblage design; water use is affected by roof assemblage design; and GHG and CED are significantly affected by floor design. The house designs with higher star ratings have lower GHG and CED emissions and higher LCC, as expected. The best design was a dwelling with weatherboard walls, a skillion flat roof and a timber/tiled floor, all at the highest star rating. House designs with modifications to just one assemblage had limited benefits in terms of life cycle environmental impacts and costs (with reductions in environmental impact up to 21%).

However, when incremental design improvements for wall, roof and floor assemblages were combined into one house design, the results showed remarkable reductions in LCA and LCC impacts (up to 43%) compared to the base case house. A small investment in construction costs yielded equal savings in operation and maintenance costs.

Several optimisation-modelling techniques were used to identify the “best” design, including graphical approach and single-objective optimisation (SOO) and multi-objective optimisation (MOO) using Mathematical Modelling linear programming (LP). A graphical approach as well as LP/SOO approach identified the same set of “best” designs, with no design best for all indicators. A graphical approach and LP/MOO approach using highest constraints also identified similar sets of best designs with no single best design. An LP/MOO approach using average constraints identified a single best design. However, the “best” design also depended on which set of indicators and weightings were selected. The preferences of the decision maker can be included when multiple indicators are considered so that a trade-off can be made. Hence, LP using a MOO approach with average constraints was found to be the most useful approach to predict a single best design amongst a wide variety of designs.

In conclusion, great savings can be made in terms of environmental impact if design of residential building envelope is optimised. Building materials have varying thermal performances, water usage and solid waste and this can be optimised only by

considering the whole building and whole life cycle context. Evaluating both LCA and LCC across a range of indicators identifies a design with a minimal increase in construction costs while delivering significant benefits to the environment. Optimisation of wall, floor and roof designs can yield a single "best" design significantly better than a conventional design using the industry standard criteria of minimum construction and operations cost. LP using a MOO approach with average constraints is the most useful optimisation approach.

DEDICATIONS

Dedicated

To

My parents who are my inspirations

ACKNOWLEDGEMENTS

I would like to express heartiest gratefulness and indebtedness to my principal supervisor, Associate Professor Margaret Jollands for her scholastic supervision, constant encouragement, inestimable help, valuable suggestions and great support through my study at RMIT University. Without her continual efforts, this would have been a very lonely journey. More importantly, she has given me great freedom to pursue independent work. She demonstrated her faith in my ability and encouraged me to rise to the occasion. In reviewing my writing, she offered painstaking comments and the ways of dramatically improving them. I have been especially fortunate to work with such a great supervisor.

I would like to express my special thanks to my second supervisor Associate Professor Sujeeva Setunge. She was strong and supportive associate supervisor of my study. She has always taken time to listen to my problems, provided insightful advice and kept me focused. She has never looked at me separately from her other research students.

I would also like to express my special thanks to Dr Nawshad Haque (CSIRO) and Dr Muhammad Bhuyan (RMIT University) who on occasion too numerous to count, provided helpful insight into life cycle assessment and optimisation techniques.

Following individuals and institutions also deserve special mention for their contributions and supports are gratefully acknowledged.

- Forest and Wood Products Australia (FWPA) for providing financial support for this research project;

- Dr. U. Iyer-Raniga and Professor R. Horne (RMIT University) for providing conceptualise initial support for this study;

- A. Carre (RMIT University) for his quick responses to my queries regarding LCA, and helping me to model my project for this study;

- Dr J. Morrissey, Dr. J. Wong and Dr. A. Kapor (RMIT University) for their quick responses, and helping me to model my project to *AccuRate* and *SimaPro* software;

- Mr D. Ashton (Mitek), Dr A. Woodard (ALCAS), Dr I. Ahmed, S. Hasan and C. Pereira (RMIT University) for their quick response to prepare bill of quantity of case study house;

- Contribution of Mr John Marshall of John Marshall builders Australia and Jerrin Designs in provision of construction documentation and finalising the assemblies is gratefully acknowledged;

- Family and friends who gave me social and intellectual support;

- At last but not the least, I feel highly indebted to my wife and other family members for their unconditional support, patience and love, which were always there for me.

ABBREVIATIONS

AAA-----------Autoclave Aerated Concrete

ABCB---------Australian Building Codes Board

ABS ----------Australian Bureau of Statistics

AGO ----------Australian Greenhouse Office

ALCAS--------Australian Life Cycle Assessment Society

ASBEC--------Australian Sustainable Built Environment Council

ASBI ---------Australian Sustainable Building Institute

ASTM---------American Society for Testing Materials

AusLCI-------Australian Life Cycle Inventory

BCA ----------Building Code of Australia

BPIC ---------Building Products Innovation Council

BRANZ-------Building Research Association of New Zealand

CH_4-----------Methane

CIE------------Centre for International Economics

CO-------------Carbon Monoxide

CO_2-e --------Carbon Dioxide Equivalent

COAG---------Council of Australian Governments

CSIRO--------Commonwealth Scientific and Industrial Research Organisation

DEH----------Department of the Environment and Heritage

DEWHA------Department of the Environment, Water, Heritage and the Arts

FC Sheet-----Fibre Cement Sheet

FWPA -------Forest and Wood Products Australia

GDP----------Gross Domestic Product

GHG---------Greenhouse Gas

GJ------------Giga Joule

GWP---------Global Warming Potential

HIA----------Housing Industry Association Ltd

ISO-----------International Organisation for Standardisation

KWh----------Kilowatt Hours

LCA----------Life Cycle Assessment

LCI-----------Life Cycle Inventory

LCIA---------Life Cycle Impact Assessment

MEPS--------Minimum Energy Performance Standards

MJ------------Mega Joule

MOO---------Multi-Objective Optimisation

MPa----------Mega Pascal

NATHERS---Nationwide House Energy Rating Scheme

N_2O ----------Nitrous Oxide

OECD--------Organisation for Economic Cooperation and Development

SEAV --------Sustainable Energy Authority of Victoria

SOO----------Single-Objective Optimisation

LIST OF PUBLICATIONS

Peer Reviewed Conference Proceedings

1. **Islam, H**, Jollands, M & Setunge, S 2011, 'Life Cycle Assessment of Residential Buildings: Quantity Take-Off and Data Input Techniques', *in Proceedings on the 7th Australian Conference on Life Cycle Assessment*, 9-10 March, 2011, Melbourne, Australia.

2. **Islam, H**, Jollands, M & Setunge, S 2010, 'Life Cycle Assessment of Residential Buildings: Sustainable Material Options in wall assemblages', *in Proceedings on Chemeca 2010: The 40th Annual Australasian Chemical and Process Engineering Conference*, 26-28 Sept. 2010, Adelaide, Australia.

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CHAPTER 1: INTRODUCTION

Background; Rationale;
Objectives; Thesis layout

1.1 BACKGROUND

Australian households largely consume energy and contribute greenhouse gas (GHG) emissions to the atmosphere. Australia's per capita GHG emissions are the highest of any OECD country (Garnaut 2008). The building sector alone contributes 19% of Australia's total energy, and 23% of Australia's total GHG emissions (ASBEC 2008). Residential building alone contributes 13% of Australia's total GHG emissions (ASBEC 2008). The construction industry also plays a vital role in the Australian economy. In 2007-08, construction activity contributed 7% to Australia's GDP (ABS 2010). The growing concern of the general population is that industry should develop in a more sustainable way.

Dwellings are built to last for several decades. Over such a long lifetime, operational use of the residence with its heating and cooling has a significant economic and environmental effect, as does in maintenance. Construction and disposal have a one-off effect, but this may also be significant. Even a small reduction in economic and environmental effects in any of the life stages would be significant when the number of dwellings is taken into account. Around 3 million new dwellings will be required in Australia by 2026 according to the Australian Bureau of Statistics and the National Housing Supply Council (ABS 2004; NHSC 2010).

Residential buildings utilise a variety of building elements in their assembly systems (i.e. floor, wall and roof). Assemblage systems are subject to constraints such as building typology, geography and local compliance. There are many variables, which creates a large range of possible designs. One variable is the material, and use of more environmentally sustainable materials in building design has been the subject of a number of studies (Blengini 2009; Woodard & Iskra 2006).

Surveys show that most people prefer environmentally friendly products if these are not more expensive than traditional products; in addition, a minority are willing to buy green products even at a higher price (Gold & Rubik 2009; Schenck 2005).

However, using environmentally friendly materials or green products in a building's design does not always minimise economic and environmental impact. If one part of a building's life cycle is overlooked, a more optimal design may be missed.

One common approach to green building design is to improve the building's energy efficiency through optimising use of materials in conjunction with insulating materials. Material assemblage options based on thermal performance may reduce the building's economic and environmental impact. However, in some climates assemblages with good thermal performance may increase the heating and cooling energy requirements (Lee, Featherstone & Robinson 2006). Similarly, optimising solely for energy may create additional environmental burdens if other impact factors are neglected, such as water usage or waste disposal options. Hence, the full environmental impact can be determined only if a variety of impact factors are considered, across the whole of the building life cycle.

Evaluating the economic and environmental impacts of a whole building over its lifetime is a complex exercise, as it requires assessment of all of its elements and all its life cycle stages. To optimise building design in terms of both economic and environmental effects, the whole building and its whole life cycle needs to be considered. Then, the influence of more sustainable material options and assemblage designs can be taken into account fully.

While many optimisation studies of buildings have been published on the building design or envelope design, relatively few have studied the effects on costing and environmental impact of building materials in assemblage and whole building design across the whole building life cycle (Blanchard & Reppe 1998; Zacharia 2003). The optimisation of materials use in floor, wall and roof assemblage designs in building whole life cycle context are still largely unexplored. Limitations of existing studies include that their outcomes are true for one particular climate or one set of regional building codes, which may be different to Australia's. Hence, an interesting area for research is to what extent such building materials can be optimised in building design to reduce economic and environmental impact.

Therefore, the aim of this research is twofold:

1) to evaluate the effect on the whole life cycle of a residential building of varying envelope materials and construction techniques, considering both economic and environmental impacts, and

2) to provide a useful optimisation framework to evaluate these effects.

1.2 RATIONALE

In terms of sustainability, low impact materials (such as renewable materials) in conjunction with conventional insulating materials can deliver great performance, depending on the circumstances. Commonly used building materials, such as timber, brick or concrete, may offer advantages such as low energy consumption during production, better thermal performance and reduced energy requirements during operation or lower energy consumption during dismantling. However, materials that have better thermal properties may in fact lead to higher energy requirements for heating and cooling in operation depending on the climate, higher impacts in the use phase due to higher maintenance, as well as higher life cycle costs. To ensure the building design is optimal, it is essential to consider materials as a building product in the building assemblage, during use in the relevant climatic conditions, including maintenance and finally disposal at the end of life management phase, as well as costs over the whole life cycle.

A number of innovative new materials have been developed recently in response to growing concern about limited resources and environmental pollution, such as autoclaved aerated concrete block, composite engineered timber (Commonwealth of Australia 2010). These new materials make it even more pressing to identify better residential building designs to reduce economic and environmental effects.

The literature lacks an evaluation of approaches to optimisation of residential buildings, applied over the whole life cycle, in terms of both environmental and economic impacts: only Zacharia (2003) included this in his study. It lacks an evaluation of how incremental changes in design of building envelope assemblages affect the impacts in different life cycle stages.

1.3 OBJECTIVES

The first objective of this research was to evaluate life cycle environment and cost impacts of a residential building with elements (i.e. floor, wall and roof assemblages) modified with different materials and construction techniques. A range of house designs with incremental improvements in star rating were assessed against a range of environmental and cost category indicators. The desired outcome was a building with low embodied and operational energy usage, low water usage, and low solid waste during and at the end of life, at lower total cost.

The second objective of this research was to identify the most useful optimisation approach to identify the best designs.

The research adopted standard assemblages for floor, wall and roof designs, based on star rating, materials and construction techniques typical for the climate of Brisbane, Australia. An LCA and LCC approach was adopted to evaluate the life cycle environmental impacts and costs effects. Various optimisation approaches were trialled to identify the best or set of best designs using a trade-off relationship.

1.4 THESIS LAYOUT

This thesis is divided into 9 chapters.

Chapter 1 introduces the background to this research topic, the research questions, rationale and objectives. In addition, it outlines the thesis layout, and introduces each chapter.

Chapter 2 reviews relevant literature on building typology, building energy rating, thermal properties of material and the environmental and economic impact assessment of buildings. It also discusses the relevant literature on LCA and LCC as well as optimisation studies relevant to buildings.

Chapter 3 discusses the tools and techniques used in this study. It discusses how to model a residential building using LCA and LCC. It also discusses how to model single or multi-objective optimisation. The software tools and methods used in this study are also critiqued.

Chapter 4 describes all aspects of the case study house, and the changes made to the case study house in terms of floor, wall and roof designs. It describes the data requirements and modelling inputs along with rationale and justification. Also, the assumptions and simplifications are discussed in detail, to enable the reader to understand and assess the validity of the results of the case study house.

Chapter 5 presents the results for the house designs with various wall assemblages while Chapters 6 and 7 present results with various roof and floor assemblages, respectively. A graphical approach is used to identify optimal designs for wall, roof and floor designs in Chapter 5, 6 and 7.

Chapter 8 presents results for optimal designs for wall, roof and floor assemblages when a Mathematical Programming (MP) model is used to optimise the design. The results are compared with the graphical optimisation approach presented in Chapters 5, 6 and 7.

Finally, Chapter 9 presents general conclusions for the work reported in this study. It also presents recommendations for future research.

CHAPTER 2: REVIEW OF LITERATURE

Introduction; Contemporary building typology; Building materials and environmental implications; Life Cycle Assessment; Life Cycle Costing; Optimisation of building design; Summary

2.1 INTRODUCTION

A residential building utilises a variety of building components in its assemblage (that is, floor, wall and roof) systems. The assemblages involve a complex arrangement of material fabricated with various technologies, meeting legislative requirements. The assemblages are produced from a wide range of resources using energy intensive processes, from raw material extraction to final disposal. Energy intensive processes consume a large amount of resources for the generation of power, and produce significant emissions and solid waste. The environmental impacts associated with building assemblages, also include operational use of the residence with its heating and cooling, as well as their maintenance and disposal. These systems also have a significant economic cost. Assessing the impact and cost of a whole building over its lifetime is a complex exercise, as it requires assessment of all its elements and life cycle stages.

To optimise building design in terms of both its economic and environmental impacts, the whole building life cycle needs to be considered so that the influence of more sustainable material options, assemblage designs, their operation, maintenance as well as final disposal are taken into account.

This chapter reviews the literature on optimisation of residential housing using Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) approaches. Firstly, this chapter discusses what are the contemporary issues in housing design, and the implications for housing assemblage design for foundation, framing, flooring, wall, and roofing. Secondly, the relationship and the significance of material selection are discussed in the context of building thermal performance and building energy rating. The product type, source, sustainability, environmental and economic implications are also discussed.

This research uses LCA and LCC as the basis to evaluate environmental and economic performance, so the significance, framework and process of LCA and LCC of buildings are also discussed. Finally, the literature on residential building optimisation studies and their implications in current practices are discussed in detail. The limitations and knowledge gap in the previous optimisation studies are also identified, and summarised.

2.2 CONTEMPORARY BUILDING TYPOLOGY

The typologies of buildings vary widely from one country to another and one area to another. Assemblage designs options also vary. The assemblage designs vary because buildings must comply with standards and policy guidelines for a particular geographical location (BCA 2005; QUT 2011). Geographic location influences heating and cooling needs during use phase (Carre 2011; Kahhat et al 2009), as climate depends on the particular geographical location.

The majority of Australia's residential buildings built since 1996 conform to the Building Code of Australia guidelines (BCA 2005). These guidelines require buildings to achieve minimum performance requirements irrespective of climate enforced through a building approval process. The building approval processes embodies Australian Standards and local by laws (BCA 2005; QUT 2011). The Standards define a minimum requirement for whole buildings including assemblies, materials and techniques for foundation, framing, flooring, roofing and wall design (BCA 2005). The Standards also specify the minimum requirements for thermal performance depending on its particular geographic location.

Conventional residential building practices also vary markedly from region to region in Australia. There are several common building systems for new housing in the Australian building industry (Staines 2004). The common wall claddings are brick veneer, weatherboard, fibre cement sheet (FC sheet), cavity brick and autoclaved aerated concrete (AAC) block. Flooring options are concrete slab on ground and suspended timber floor. Roofing options includes flat or pitched within hip, gable and skillion types (QUT 2011).

Some builders and designers use more than one assemblage option in the same design. Some prefer to use brick veneer or lightweight claddings (that is weatherboard or FC sheet). Popular assemblage designs are brick veneer/double brick, timber frame with concrete slab on ground or timber sub-floor; light weight concrete block, timber frame on concrete slab; timber frame with lightweight cladding on concrete slab or timber sub-floor (Staines 2004).

The external claddings generally act as façade that is anchored with a frame (Staines 2004). Timber is commonly used for framing where it bears the structural load of entire roof, ceiling and wall lining (Kapambwe et al 2008). Corrugated metal and tile are used in rooftops. Timber, carpet and tiles are commonly used for floor tops. All these options use wide ranges of materials, construction techniques, and incorporate different local guidelines (QUT 2011).

2.2.1 Foundation and framing

Foundations of a building must conform to Australian Standards (AS 2870). According to Standards Australia, the design must be sufficient to support the loads safely. Additionally, it must be capable of resisting the sliding, uplifting and overturning associated with local wind and seismic conditions (Standards Australia 2011).

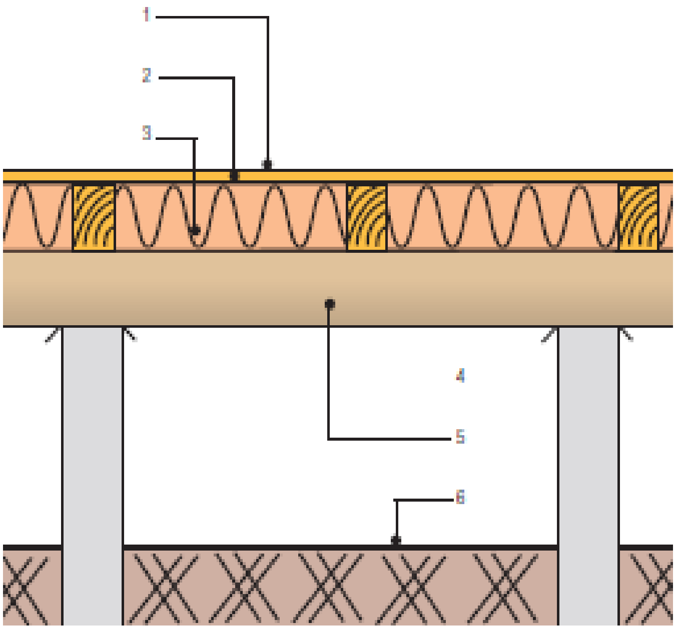
The framing materials can be either pre-cut and pre-nailed at the factory or just pre-cut at the factory and assembled on site (Staines 2004). Seasoned or unseasoned timber is used for framing generally. According to Kapambwe et al (2008), in Australia, 74% of dwellings have timber wall framing and 89% of dwellings have timber roof framing. A recent development is the use of manufactured shapes and engineered timber products in framing applications, which are replacing traditional timber framing in the residential building sector (Kapambwe et al 2008; Lawson 1996).

2.2.2 Floor

Two types of floor are commonly used in Australia: suspended timber floor and concrete slab on ground (Kapambwe et al 2008; QUT 2011; Staines 2004). The cross sectional views of these floor types are shown in Figure 2.1 and Figure 2.2. Builder and designer use various materials and techniques in assemblage designs. Popular flooring tops are carpet, bared timber, carpeted timber and carpeted tiles (FWPRDC 2002). In recent years, autoclaved aerated concrete (AAC) floor panel is also used

(ICANZ 2009). Popular floor decks are plywood and particleboard. The installation of timber flooring over a concrete slab is also common in newly built houses (FWPRDC 2001).

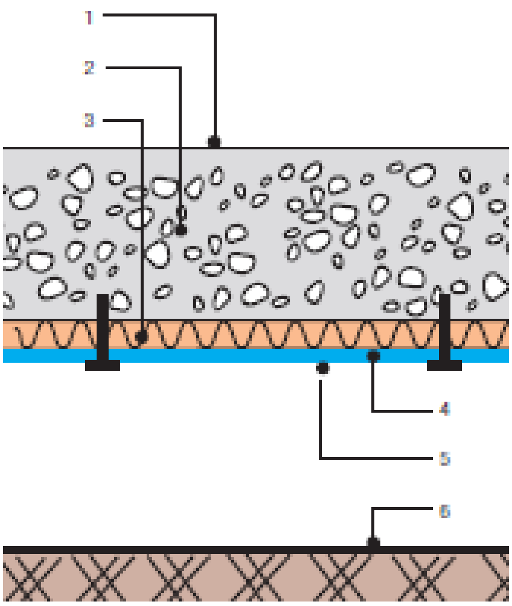
Figure 2.1: Suspended timber floor (ICANZ 2009)



<u>Suspended Timber Floor</u>

1. Indoor Air Film
2. T&G Timber Floor (19mm)
3. Unventilated Air Space
4. Reflective Insulation Material
5. Sub floor Reflective Air Film
6. Ground Thermal Resistances

Figure 2.2: Concrete slab on ground (ICANZ 2009)



<u>Concrete slab on ground</u>

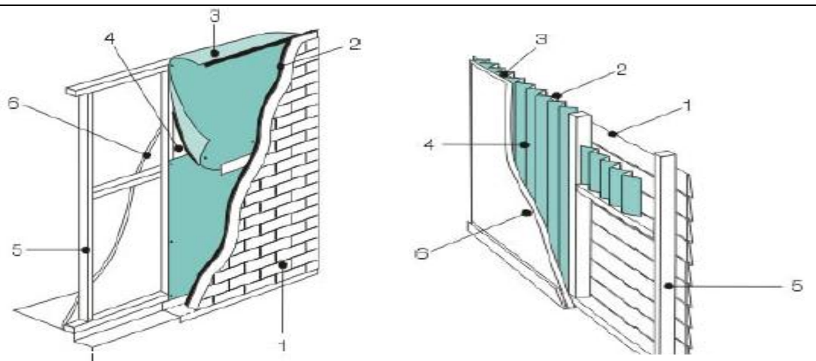
1. Indoor Air Film
2. Concrete Slabs (150 mm)
3. Unventilated Air Space (50mm)
4. Reflective Insulation Material R-value
5. Unventilated Sub floor Reflective Air Film
6. Ground Thermal Resistances

In terms of thermal performance, the fixing method varies within floors types. BCA gives advice on the fixing method, including the variation of insulation type, thickness, placement and air space (BCA 2005). These should be a minimum air cavity between floorboards and foil (ICANZ 2009). In suspended timber floor, reflective insulation material is fixed on the under-sides of the joists. In concrete slab on ground design, the insulation is pinned to the under-side of the slab (ICANZ 2009). It maintains a minimum air cavity between the concrete slab and foil (ICANZ 2009).

2.2.3 External Wall

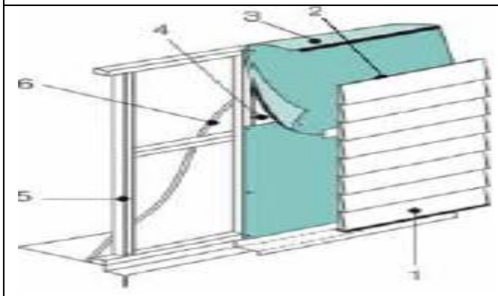
Australian housing construction uses various types of external cladding (FWPRDC 2002; QUT 2011). Some common wall options are shown in Figure 2.3, Figure 2.4 and Figure 2.5.

Figure 2.3: Common wall options (FWPRDC 2002)



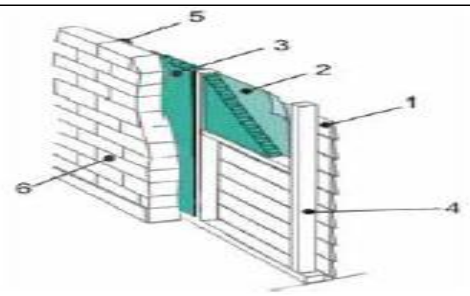
Brick/Block Cladding **Weatherboard Cladding**

1. External cladding
2. Airspace (non-reflective)
3. RFL
4. Airspace (reflective)
5. Timber studs Frame
6. Plasterboard 10 mm



FC Sheet/Plywood cladding

1. FC sheet cladding 2. Airspace (anti-glare)
3. Permeable (RFL) 4. Airspace (reflective)
5. Timber studs 6. Plasterboard 10 mm

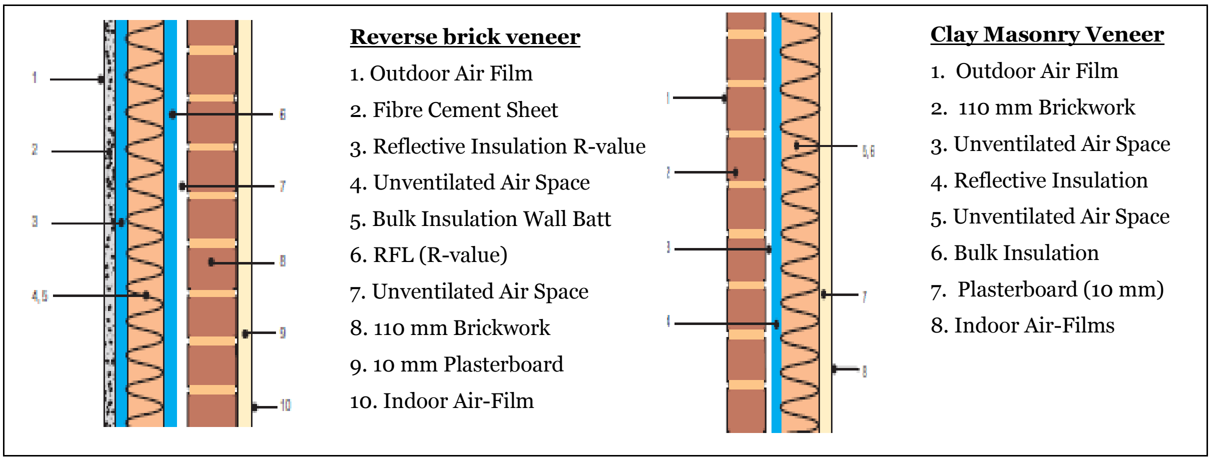


Reverse brick & timber cladding

1. External cladding 2. Building membrane
3. Bulk insulation 4. Timber studs Frame
5. Airspace 6. Brick internal cladding

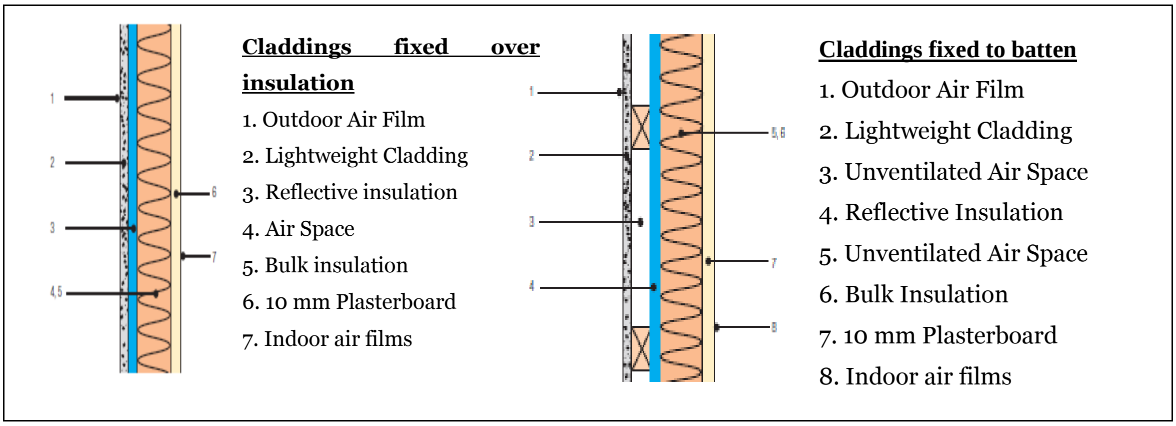
These include brick or block cladding with or without bulk insulation; reverse brick veneer-weatherboard, plywood or fibre-cement cladding; weatherboard, plywood or fibre-cement cladding; weatherboard or sheet cladding, clay masonry veneer. These are insulated to improve thermal performance in wall assemblage designs. The variation reflects the builder's preferences for different assemblage designs. It also reflects the customer preferences for cladding types.

Figure 2.4: Reverse brick and clay masonry veneer wall (ICANZ 2009)



These figures illustrate the fundamental differences among the wall elements and assemblage design techniques. Figure 2.3 shows that several combination claddings are used on wall options. Figure 2.4 shows that brickwork is used on both the outer or inner side of an exterior wall. Figure 2.5 shows how lightweight external claddings are fixed to stud or insulation. The insulation is usually fixed with its edges to the stud. The cavity of the frame is also filled with insulation. External claddings may be fixed directly over reflective insulation or timber stud. The insulation is usually attached with either one edge or both edges over stud.

Figure 2.5: Lightweight cladding fixed over insulation or stud/batten (ICANZ 2009)



The literature reports a long-term shift from timber to brick as the most popular outer wall cladding. According to the Australian Bureau of Statistics, 55% of dwellings had timber outer walls in 1911 while 71% of new dwellings had brick outer walls in 1999 (ABS 2001; Kapambwe et al 2008). However, there is not just brick and timber;

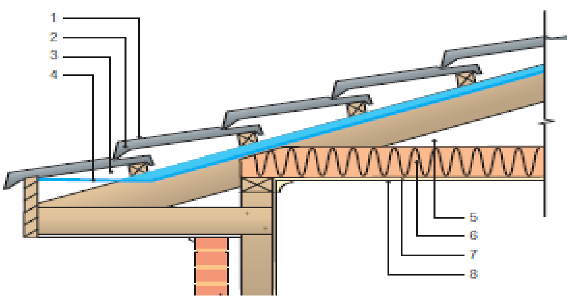
the market share is also increasingly going to hollow concrete block and concrete tilt slab. Lightweight cladding (with or without cavities) is also used more frequently in wall assemblage designs in recent years (ICANZ 2009).

The long-term shift from timber to brick may contribute overall environmental and economic benefits either positively or negatively. To determine which, all the materials used in a building should be accurately evaluated over the whole building life (Blengini 2009; Woodard & Iskra 2006).

2.2.4 Roofing

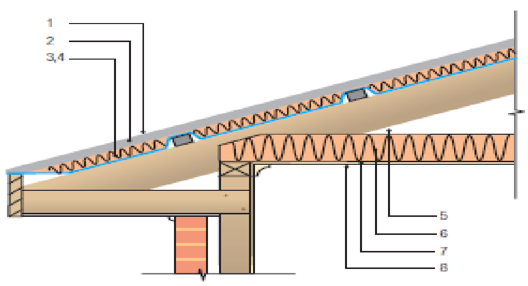
Many roofing options (flat or pitch roof) are used in Australian housing (Staines 2004). A pitched roof with flat ceilings is one of the most popular (FWPRDC 2002). The cross sectional views of two options for a pitch roof with flat ceiling is shown in Figure 2.6. Tile and metal are common options for rooftop material. Timber and plasterboard are the most common for roof framing and ceiling (Kapambwe et al 2008; QUT 2011). The ceiling linings are fixed directly to the underside of timber ceiling joists. The ceilings act as part of the roofing envelope.

Figure 2.6: Pitched roofs with flat ceiling options (ICANZ 2009)



Tile Roof

1. Outer Air-Film
2. Tiled roof
3. Air space
4. RFL Insulation
5. Attic space
6. Ceiling insulation
7. Plaster board
8. Indoor Air-Film

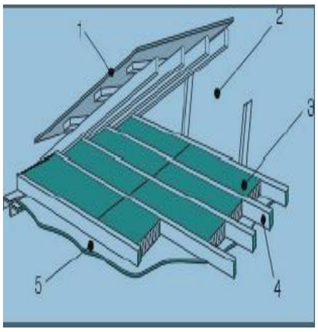
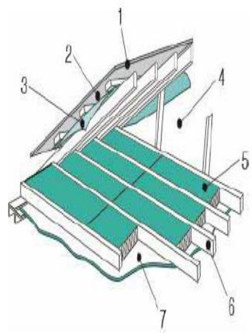
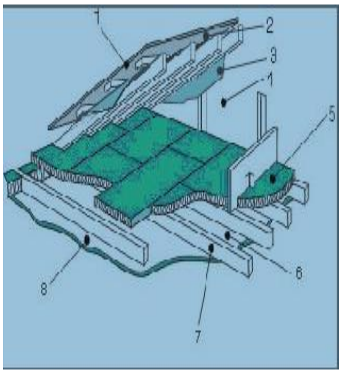
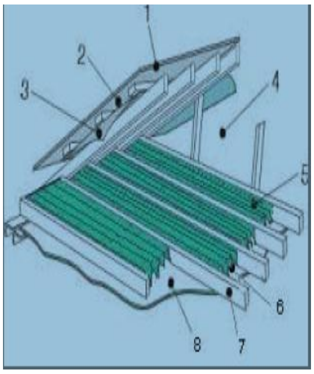


Metal Roof

1. Outdoor Air Film
2. Metal roofs
3. Air Space
4. Reflective Insulation
5. Attic Space
6. Ceiling Insulation
7. Plasterboard
8. Indoor Air-Films

To improve thermal performance, roofing materials are usually assembled in conjunction with insulation, regulated by Australian Standard AS-1562 (Standards Australia 1992). Figure 2.7 shows a sample of available roof assemblage designs including how insulation is fixed. Insulation is attached under the rooftop where it is placed under battens or draped over battens. It is also attached above the ceiling linings. In the ceilings, insulation is placed either over the joists, or between the joists. Some builders also use additional reflective insulation (Reflective Foil Laminates-RFL) over bulk insulation (FWPRDC 2002).

Figure 2.7: Sample roof assemblage designs options (FWPRDC 2002)

 1. Roof cladding 2. Attic space 3. Bulk insulation 4. Ceiling joists 5. Plasterboard **Insulation in ceiling only**	 1. Roof cladding 2. Attic space 3. RFL 4. Attic space 5. Bulk insulation 6. Timber ceiling joists 7. Plasterboard **Insulation in ceiling and rooftop**
 1. Roof cladding 2. Air space 3. RFL 4. Attic space 5. Bulk insulation 6. Air space 7. Ceiling joists 8. Plasterboard **Insulation over joists**	 1. Roof cladding 2. Air space 3. RFL 4. Attic space 5. Bulk insulation 6. Air space 7. Ceiling joists 8. Plasterboard **Insulation under rooftop and between joists**

In summary, the assemblage designs for floor, wall and roof vary widely across Australia's large continent. A wide range of materials and construction techniques are used depending on building preferences as well as climate. The outcomes from one region will not be directly applicable to another region.

2.3 BUILDING MATERIALS AND ENVIRONMENTAL IMPLICATIONS

2.3.1 Resources used in buildings

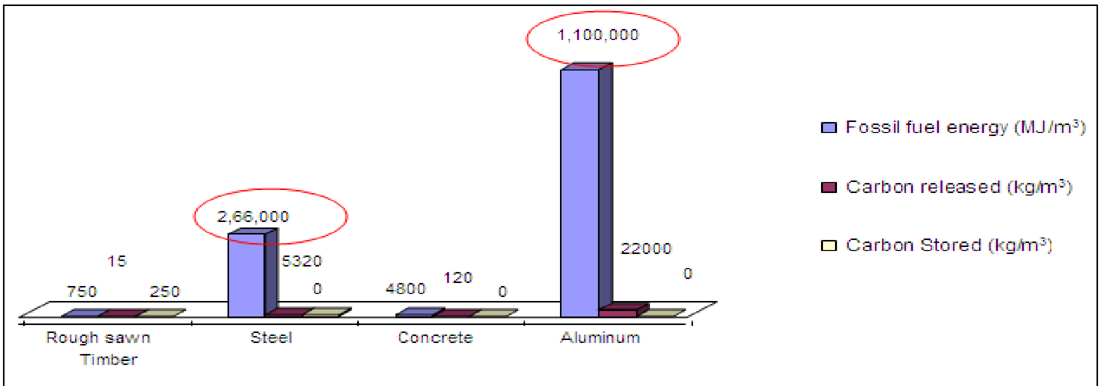
Globally, the building industry accounts for 16% of the world's fresh water usage, 25% of its wood harvest and 40% of its materials and energy flows (Bilec 2007). The most common building materials are timber, brick and concrete. In Australia, construction accounts for 55% of timber use, mainly for residential buildings (Newton et al 2001).

Building assemblies encompass many processed materials. Processed materials are manufactured from raw materials using energy, and producing waste. The raw materials for timber generally come from forests. In Australia, the production process consists of harvesting of logs, transportation, sawmilling and drying (Lawson 1996). The raw material for concrete generally comes from mining (that is natural gravels, crushed rocks, sands and aggregate). The production process consists of mining, transportation, crushing and grinding (Lawson 1996). Hence, the production of materials as different as timber and concrete is similar in complexity, and both have energy intensive steps.

2.3.2 Environmental implications of building material

Building materials involve energy intensive steps. Before reaching the construction site, the manufacture of building materials requires raw material extraction, transportation, processing and manufacturing process to produce a finished product. A major issue is that a large amount of renewable or non-renewable fuel may be required for the production processes. These produce many environmental impacts (Ferguson et al 1996; Lawson 1996). Another issue is transporting the building materials to the construction site can generate substantial energy inputs. The impacts vary in type and magnitude. For example, each tonne of cement production generates 1 tonne of CO_2 and 20 kilograms of dust, and each tonne of steel product generates 2 tonnes of CO_2 (Lawson 1996).

Figure 2.8: Environmental profile of manufactured product (Ferguson et al 1996)



Environmental Profile of Manufactured Materials

Figure 2.8 shows the relative environmental profile of some popular manufactured building materials and their carbon release and storage. Manufactured aluminium and steel do not store any carbon and use very significant amounts of fossil fuel energy (ringed). On the other hand, timber stores carbon as well as using much less fossil fuel.

Figure 2.9: Energy consumption profile of building elements (Williamson et al 2001)

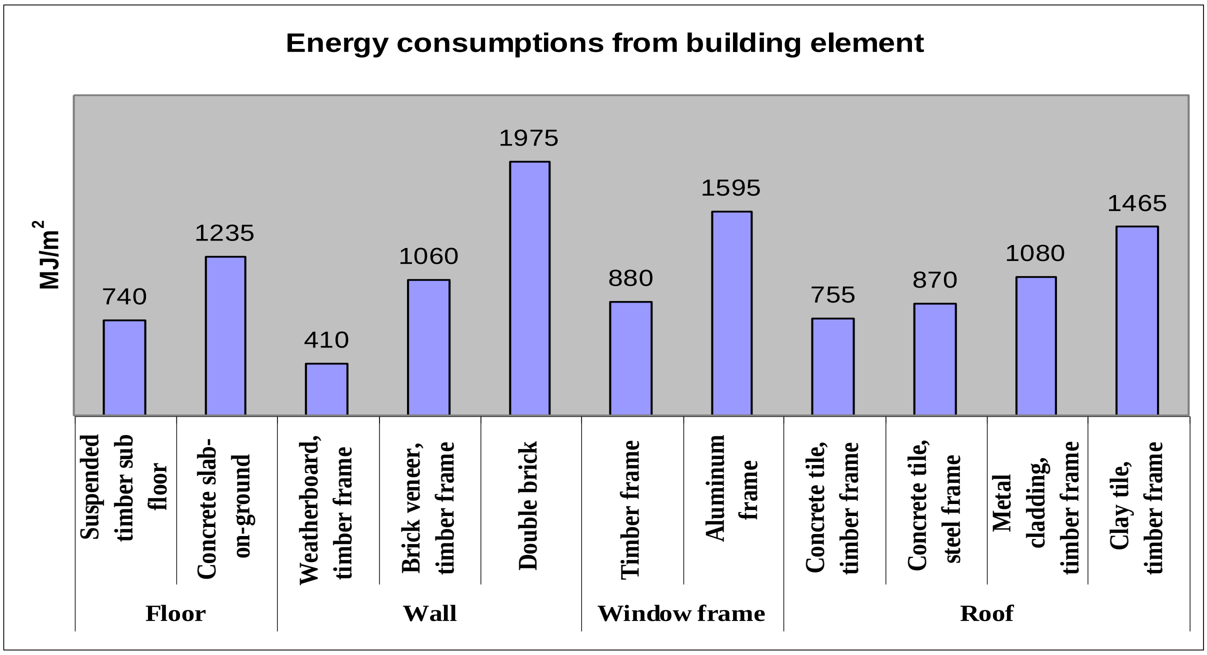


Figure 2.9 shows the relative embodied energy consumption of different building elements per square meter basis. It indicates that timber materials used in floor, wall and roof assemblages require significantly less primary energy input value.

Neither comparison provides cumulative impact across the whole building life cycle nor does such a comparison give due consideration to the purpose or functional unit basis. Therefore, this comparison may mislead the consumer into selecting an inferior material when the building whole life cycle is considered. The use phase (that is space heating and cooling), maintenance and end of life management or disposal together contribute to the gross impact (Adalberth et al. 2001). Therefore, the material is comparable when considering its usages as building component.

2.3.3 Selection of material for building sustainability

The correct choice and substitution of less with more sustainable products can reduce the environmental footprint of buildings (DEH 2006; Szalay 2007; Thormark 2006). There is a general view that 'closing the sustainability gap' can be achieved by using as few non-renewable resources as possible, by generating as little waste as possible, and by using renewable resources at a rate less than their generation rate (Ljungberg 2007; Zacharia 2003). Similarly, there is a view that this simplistic approach ignores the thermal efficiency of materials in a building product or building assemblage, the operation/use, maintenance, and end of life management phases, that impact over the building life cycle phases. In order to assess environmental sustainability issues, the assessment method should include the impacts of cumulative consumption across the building's whole life cycle (Ding 2007; Mithraratne & Vale 2004). The effects on environmental impact of substitution of materials may be positive or negative, depending on climatic conditions (Carre 2011; Lippike et al 2004).

2.3.4 Thermal comfort and energy efficiency of building

Householders have goals of high thermal comfort throughout the year. In many areas in Australia, the temperature moves out the comfort range due to the large diurnal ambient temperature ranges as well as the large variation in daily average over the year (Ballinger 1988; Commonwealth of Australia 2010; SEAV 2002). The problem of comfort in locations like Sydney and Brisbane is due to overheating across much of the year. The problem of comfort in locations like Hobart and Melbourne is due to under heating in winter (Ballinger 1988). These comfort differences are often reflected in building typology and climatic requirements for heating and cooling.

The general rule for optimising the comfort of occupants and energy efficiency in a building is to provide the lowest comfortable temperature in winter and the highest comfortable temperature in summer (SEAV 2002). In winter, residential buildings lose an average of 10% of heat through the floor, 60% through the roof, and 30% through the walls (FWPRDC 2003), which requires additional heating to achieve the desired thermal comfort. Heat loss is minimised by a 'tight design' (such as airtight windows).

A building also needs air exchange for the occupants comfort in summer. The well fit of roofs, floors, doors and windows significantly influence the building thermal comfort (Elmroth & Levine 1983; Santamouris et al 1996; Zacharia 2003) because a well-designed ventilation system can save a considerable amount of cooling load from all condition in summer (up to 30%) by using air exchange at night (Santamouris et al 1996).

2.3.5 Thermal mass and climate

Heating and cooling requirements dependence on thermal mass properties of building components has been studied extensively (Commonwealth of Australia 2010; SEAV 2002; Williamson et al 2001; Woodard & Iskra 2006). The appropriate use of thermal mass throughout a building can reduce heating and cooling requirements and increase thermal comfort (SEAV 2002; Thiers & Peuportier 2008). Thermal mass acts as a thermal storage. It absorbs heat during summer days keeping the house cooler, releasing the heat at night if there is ventilation (SEAV 2002). Conversely, the same thermal mass can store heat from the sun or heaters during the winter days, keeping the home warmer in winter.

Thermal mass of a building is particularly beneficial where there is a big difference between day and night outdoor diurnal temperatures (Commonwealth of Australia 2010; SEAV 2002). As a rule of thumb, if diurnal temperature ranges exceed 10°C then high thermal mass construction is desirable. Sub-tropical climates like Brisbane have a diurnal range of 7-8°C, so, high thermal mass construction can cause thermal discomfort unless carefully designed with shade and insulation. Besides these, in extreme climates (cool or cold) like Melbourne, where supplementary heating is often used, houses will get benefit from high thermal mass construction regardless of a small diurnal range (Commonwealth of Australia 2010).

2.3.6 Energy efficiency, DTS and star rating provisions

The BCA introduced incentives to improve energy efficiency in buildings by adopting a house energy rating scheme and Deemed-to-Satisfy (DTS) provisions (ABCB 2010). The house energy-rating scheme (star rating) is a benchmarking scale where the more stars, the more energy efficient the building is. In Australia, most states and territories had adopted a minimum rating of 3.5–4 stars for new houses in July 2003. It was increased to 5-stars in 2006 (McLeod & Fay 2010). However, since May 2011, all new homes, additions and alterations must now achieve a 6-Star energy rating in Australia (Building Commission 2011).

In Australia, the DTS provision was an alternative to the star ratings until May 2011. Therefore, the BCA has set new DTS provisions incorporating energy efficiency compliances and requirements. The DTS provisions contain a range of practical, commonly used and cost effective building solutions such as insulation in roofs, walls and floors, glazing of low solar heat and conductance characteristics (ABCB 2010). It also includes shading, energy efficient air conditioning and energy efficient lighting.

There are various computer software tools to rate the energy efficiency of Australian homes. Table 2.1 illustrates the rating tools commonly used in Australia. Rating tools estimate the yearly heating and cooling loads of the building design and provide a star rating (GBCA 2008).

Table 2.1: Commonly used building thermal performance rating tools in Australia

Tools and Origin	Characteristics
AccuRate (CSIRO)	• The new version of *NatHERs* since 2006 • It rates homes in tropical and sub-tropical climate • It provides efficiency rating (0 to 10 stars) • It includes an extensive database of materials • It allows users to modify construction elements • It considers design, construction, orientation, insulation
FirstRate5 (Sustainability Victoria, Australia)	• It provides efficiency rating (0 to 10 stars) • It includes an extensive database of materials • It considers design, construction, orientation, insulation • It allows users to modify construction elements
NatHERS CSIRO	• Computer-based housing energy rating system • It provides energy efficiency rating (0 to 5 stars) • It links to location climate information • It considers design, construction, orientation, insulation
Green Star (Australia) Green Building Council	• Australia's first comprehensive method for evaluating environmental building performance • It provides efficiency rating (0 to 6 stars) • For commercial buildings only

The star rating of buildings depends on their thermal performance efficiency. Several studies reported that thermal performance of a building component could be improved by adding insulation (DEH 2006; Zacharia 2003). According to the Sustainable Energy Authority Victoria (2002), approximately 45–55% of heating and cooling energy can be saved by using effective insulation. Insulation can be used in walls, under floors and ceiling or roofing to make significant impact and energy savings for whole buildings (ICANZ 2009).

2.3.7 Environmental impacts of buildings

A range of environmental impacts of building was evaluated in previous studies. Among them, environmental burdens associated with global warming potential (GWP) and energy consumption are common (Blanchard & Reppe 1998; Ortiz et al 2008; Rouwette 2010). GWP expresses the overall contribution to climate change of all greenhouse gases (GHG) emitted during a fixed time, such as 100 years (IPCC 2007; Zacharia 2003). The major GHG are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The GHG are added together to provide one single value of GWP. GWP is represented as carbon dioxide equivalent (CO_2 e) impacts.

Energy consumption of buildings refers to the life cycle primary energy consumption for production, use and disposal (Szalay 2007). Several authors reported life cycle primary energy consumption as cumulative energy demand (CED) (Carre 2011; Rouwette 2010; Szalay 2007). CED does not distinguish between various forms of primary energy (Rouwette 2010).

A sophisticated software tool is needed if a broad range of impact categories is investigated. There are numbers of assessment tools available to evaluate environmental impact of buildings more broadly. Life Cycle Assessment (LCA) is an internationally agreed tool to evaluate environmental impacts. The significance of LCA, LCA tools and LCI database, environmental impact indicators are discussed in detail in the next section.

2.4 LIFE CYCLE ASSESSMENT

2.4.1 Overview of LCA approach

ISO 14040 defines LCA as the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its lifecycle" (ISO 2006, pp. 2). LCA is a broad term, which covers a number of approaches as a way of thinking, and could be applied to any situation where consideration of impact over time is important (Henriksen 2006). LCA is a system analysis method evaluating the environmental aspects and potential impacts associated with a product, process, or service (Guinee et al 2002; Nissinen et al 2007; Xing et al 2008).

LCA encompasses the original sources of raw materials; distribution and transportation processes; use and maintenance of products; process wastes; and product reuse, recycling, energy recovery, product disposal, processes and flows (ARUP 2006; Guinee et al 2002; Nissinen et al 2007; Xing et al 2008).

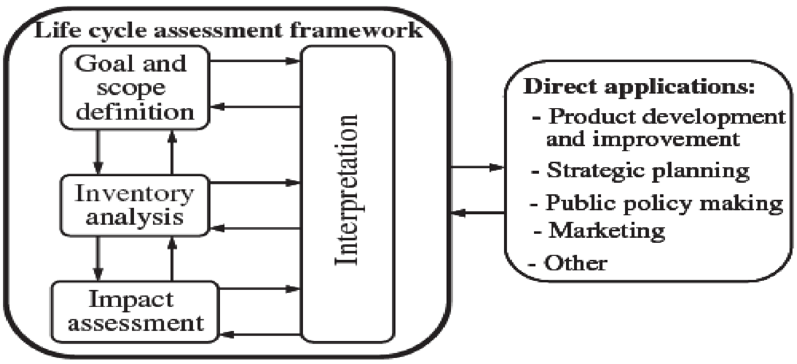
2.4.2 Methodological Framework of LCA

LCA consists of four distinct analytical steps: (1) goal definition and scope; (2) life cycle inventory (LCI) analysis; (3) Life Cycle Impact Assessment (LCIA); and (4) interpretation of results. The framework and various stages of LCA are shown in Figure 2.10.

2.4.2.1 Goal Definition and Scope

Goal definition and scope examines how the functional unit is used, and what procedures are followed (Ardente et al 2008; Ortiz et al 2008; Roy et al 2009). It defines how results are reported, and which comparisons are drawn between products and services (ARUP 2006). It identifies the audience, and determines the systems boundaries (Ortiz et al 2008; Roy et al 2009). However, there is no guidance on which comparisons should be undertaken or what should, and should not be included in LCA (ARUP 2006; Carre 2011). The product function and functional unit are central elements to define the scope of the LCA study (ARUP 2006; ECJRC 2009; Hauschild 2005; Rebitzer et al 2004).

Figure 2.10: Stages and application of LCA (ISO 2006)



Choice of the functional unit is guided by needs: the unit must provide similar functions even if provision of the functions is achieved through different products and services (ECJRC 2009). Comparisons are then made based on functional unit only rather than product or service.

A systematic approach must be taken to define the functional unit (ARUP 2006; Carre 2011). It should be comparable to those of other systems serving the same functions. Comparing two doors made from different materials is meaningful if the same door installed at the same location (ARUP 2006). Conversely, comparing an external door with an internal door will not be meaningful if the two doors are of the same size, as the environmental conditions are different. For example, typical functional unit for LCA studies of building are 'per square meter' or 'per house' or 'certain area of floor for a particular usage for a certain time' could be the functional unit used to compare house designs (ARUP 2006; Carre 2011).

ISO 14044 standards recommend drawing a technical process flow diagram as this will help to clarify what the object of the LCA study is and help construct the systems boundary (ECJRC 2010). The diagram should include as many elementary flows as possible to perform a detailed assessment. The inputs are raw materials, energy and water. The outputs are the products and co-products, and emission to air, water and soil (ISO 2006; Roy et al 2009). The process flow includes all the inputs and outputs from the processes within a system boundary (CWC 2004).

The system boundary can then be drawn as it includes the major input and output flows (ISO 2006; Roy et al 2009). To achieve robust and defendable LCA outcomes, the system boundary and assumptions must be justified (ECJRC 2009). Grant & Carre (2009) suggest three rules when setting system boundaries. Firstly, system boundaries should cover the same 'reality' in all scenarios. Secondly, the relevant raw material extractions and any screening processes (i.e. extraction of gravel for concrete) may be a useful focus. Finally, identical processes should be excluded if the reference flows are equal. If the same systems boundary process is followed the LCA results for the same product or process will be similar as long as the assumptions are also similar (Carre 2011; ECJRC 2009).

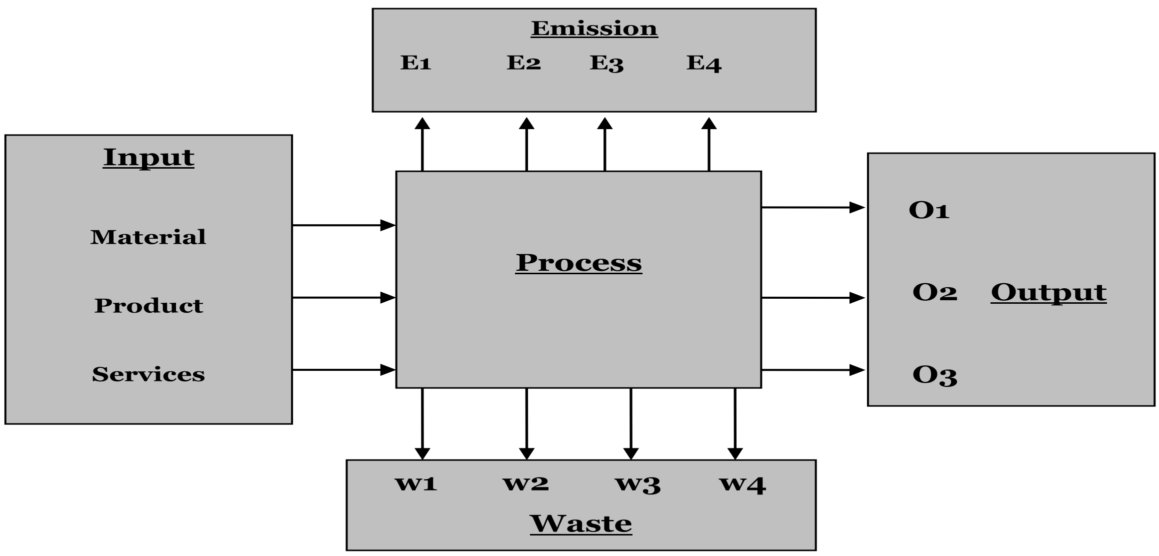
2.4.2.2 LCI Analysis

The most cited bottleneck of LCA studies is the availability of valid LCI data (Horvath 1997; Reap et al 2008; Szalay 2007). Fortunately, data for the most common building products and processes, such as transportation, extraction of raw materials, processing of materials and disposal, are available in international LCA databases. However, they may require adjustment before being use in a local context (CWC 2004; Roy et al 2009; Szalay 2007).

The outcome of LCI analysis is a quantitative list. It contains all the relevant inputs (energy, mass flow) and the outputs (emissions) of the systems in all the life cycle stages (Ortiz et al 2008; Roy et al 2009; Wang 2005). LCI analysis involves recording and tracking inflow and outflow of the resources and wastes for specific products or processes (Ortiz et al 2008; ECJRC 2009; Wang 2005). The data are documented based on relevant environmental flows associated with the product or process (ARUP 2006).

There are several LCI modelling frameworks (Carre 2011; ECJRC 2009; ISO 2006). The choice of the most appropriate LCI modelling framework is made on a case-by-case basis. The European Commission Joint Research Centre (ECJRC) recommends selecting a fundamental LCI principle at an early stage of the goal and scoping definition (ECJRC 2009). A key determinant of the best framework is the complexity of the multi-functional process. A multi-functional process requires an appropriate LCI modelling framework (ECJRC 2009; Guinee et al 2002; Yellishetty et al 2009). A sample multi-functional process is shown in Figure 2.11.

Figure 2.11 : A Multi-functional process



The inputs and outputs of the process are shared quantitatively among several different deliverable goods or services. ISO identifies three steps in an 'allocation' hierarchy (ECJRC 2009; ISO 2006; Rebitzer et al 2004) to solve this multi-functionality. Firstly, expand the system boundary to include all the additional functions related to the co-products including the co-products that yield comparable outputs. Secondly, allocate the inventory based on causal relationships, and the inputs and outputs are changed quantitatively. Thirdly, allocate the products and functions based on value, mass or volume or other measure (ECJRC 2009).

After completing the LCI, Life Cycle Impact Assessment (LCIA) methods are used to calculate the impact category indicators. In the following section, LCIA methods are reported.

2.4.2.3 Life Cycle Impact Assessment (LCIA)

The outcome of any LCA is to evaluate the potential environmental load. There is no single agreed LCIA method in Australia or around the world (Grant & Peters 2008). ISO 14044 provides a standardised guideline for LCIA.

Various region specific LCIA methods are available in LCA software tools. The most commonly used LCA software program, *SimaPro,* contains several LCIA methods. Many of these are specific for the Australian region. These include the Australian impact method with normalisation; Australian Impact method with normalisation including Cumulative Energy Demand; Eco-indicator with Australian adjustment; CML 2 baseline 2001-Australian toxicity factor; EDIP with Australian substance; and Impact 2002+ with Australian substance added. The main variation among the different LCIA methods is range of impact category indicators (ARUP 2006; Grant 1999; ISO 2006; Ortiz et al 2008). Therefore, the choice of LCIA methods depends which environmental issues are required for the particular study.

All LCIA methods have three mandatory elements and four optional elements (ARUP 2006; Grant 1999; ISO 2006; Ortiz et al 2008). The mandatory elements are impact category, classification and characterisation. Sample of typical life cycle impact categories, classifications and characterisation are shown in Table 2.2.

Table 2.2: Typical life cycle impact category, classifications and characterisations

Impact Category	Classifications	Characterisations
GWP (Global Warming Potential)	Carbon Dioxide (CO_2) Nitrogen Dioxide (NO_2) Methane (CH_4) & CFCs	Convert LCI data to CO_2 equivalents (CO_2 e)
Acidification potential	Sulfur Oxides (SO_x) Nitrogen Oxides (NO_x) Ammonia (NH_4)	Convert LCI data to hydrogen (H+) ion equivalents
Eutrophication	Phosphate (PO_4) Nitrogen Oxide (NO) Nitrogen Dioxide (NO_2) Nitrates, Ammonia NH_4	Convert LCI data to phosphate (PO_4) equivalents
Land Use	Quantity disposed of in a landfill	Convert mass of solid waste into volume using an estimated density
Human Health	Total releases to air, water, and soil	Convert LC50 data to equivalents

Classification is the process to categorise the impacts into various impact categories (ARUP 2006; Hamilton et al 2008; Roy et al 2009). For example, the impact of emissions of CO_2, NO_2, CH_4 is on global warming, so these are classified into global warming potential (GWP). GWP is the impact category.

Characterisation is the process to characterise each impact quantitatively with a common unit (ARUP 2006; ISO 2006; Roy et al 2009). This allows the effect of the impacts to be summed. For example, different greenhouse gases are converted into CO_2 equivalent (CO_2 e). These are then added together to represent the global warming potential (GWP). Table 2.3 shows some values how GHG emissions were converted to GWP (ECJRC 2007; IPCC 2007).

Table 2.3: GWP of Greenhouse Gases (IPCC 2007)

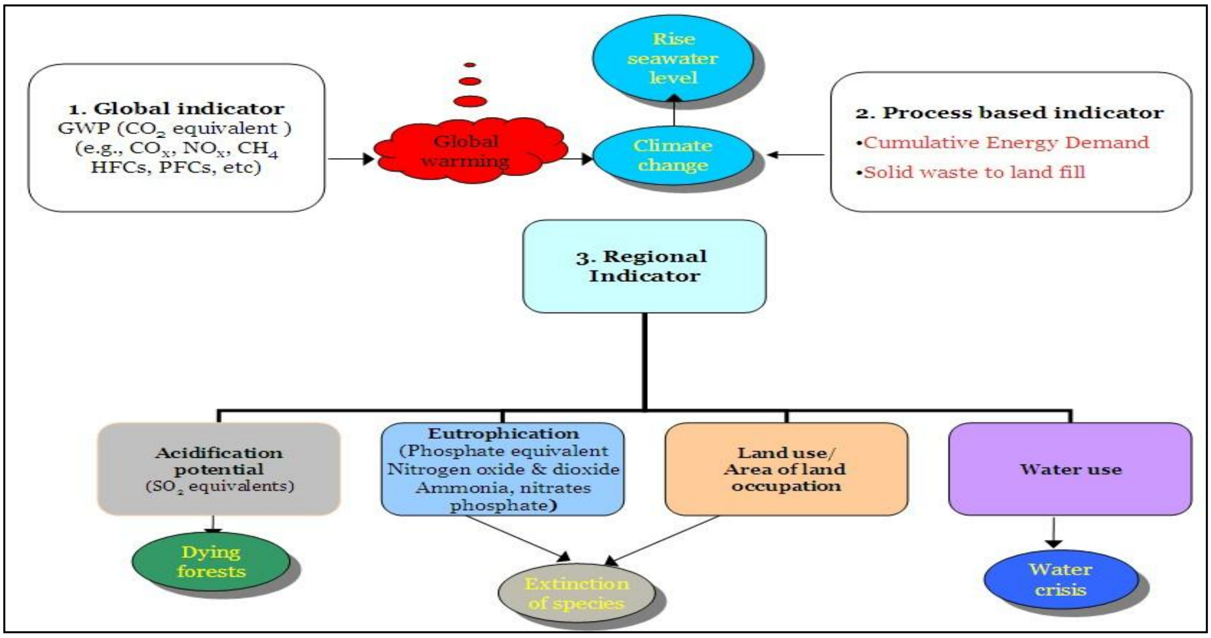
Name	GWP_{100}
Carbon dioxide CO_2	1
Methane CH_4	25
Nitrous oxide N_2O	298
HFCs	124 - 14800
Sulphur hexafluoride SF_6	22800

GWP is calculated over a specific time interval. GWP_{100} refers to 100 years interval. For example, the 100 years GWP of CO_2 and CH_4 are 1 and 25 respectively. 100 years of time horizon is commonly used (IPCC 2007).

The four optional elements are normalisation, grouping, weighing and data quality analysis (ARUP 2006; Finnveden 1999; Guinee et al 2002; Ortiz et al 2008; Roy et al 2009). Normalisation represents the potential impact in such a way that all impacts can be compared on the same scale. To obtain a normalised LCIA result, the result is multiplied by a normalisation factor (ARUP 2006; ISO 2006; Roy et al 2009). The normalisation factors shown in Table 2.3 are used to calculate the GWP. Grouping ranks the impact categories (ARUP 2006). However, it does not add any substantial value in practice because it only sorts the impacts (ARUP 2006; ECJRC 2009). Data quality analysis aims to validate the LCIA results (ARUP 2006; Roy et al 2009).

The various impact category indicators are broadly grouped into global, process based and regional indicator (Grant & Carre 2009; Roy et al 2009). Figure 2.12 shows 3 broad impact category indicators of LCA and their effects.

Figure 2.12: Impact category indicators of LCA and its effects



The global indicators have the effects on global warming, climate change and sea level rise. The process-based indicators include cumulative energy demand and waste to landfill (Grant & Carre 2009). The process-based indicators have also effects on global warming, climate change and sea level rise. The regional indicators include acidification, eutrophication, land use, water use, carcinogens, eco-toxicity and human toxicity (Roy et al 2009). The regional indicators have effects on water crisis, extinction of species and dying of forests shown in Figure 2.12.

2.4.2.4 *Interpretation of Results*

The LCI and LCIA results are discussed in the interpretation stage. The results are discussed in terms that are consistent with the defined goal and scope (ARUP 2006; Roy et al 2009). The results should be reported in a neutral and informative manner to identify the significant issues, which are evaluated to reach conclusions and formulate recommendations (Hamilton et al 2008; Ortiz et al 2008; Roy et al 2009).

The assessment of results should include both quantitative and qualitative measures (Hamilton et al 2008; Roy et al 2009). Sensitivity and uncertainty analysis may be undertaken to qualify the results and to reach conclusions more confidently (Hamilton et al 2008; Hauschild 2005).

2.4.3 LCA and LCI initiatives

Several different versions of LCA software have been developed in different regions, such as *GaBi* and *SimaPro* in Europe, and *ATHENA* in US and Canada (Szalay 2007).

Table 2.4: LCI databases around the world (Hammond & Jones 2008; Tharumaharajah & Grant 2006

Database	Source	Region	Focus
Eco-Invent 2000	Primary, BUWAL, ETH-ESU	Swiss & Western Europe	Generic; over 2500+ processes; includes uncertainty data & infrastructure
Athena	Primary	Canada & North America	Construction industry; 90+ processes–wood, steel, concrete & structural products
USA National LCI	Primary, Eco-Invent 2000	USA & North America	Basic processes to build upon in LCA studies
Australian LCI	Primary, various databases	Australia	Mostly AusLCI and LCA studies at RMIT/Centre for Design and others
Canadian database	Primary	Canada & North America	Basic materials: aluminium, glass, plastics, steel and wood
Inventory of Carbon and Energy (ICE)	Secondary	Global	To create an inventory of embodied energy and carbon coefficient for building materials

LCA software tools contain life cycle inventory (LCI) databases of locally manufactured products. There are many LCI databases available around the world. Examples of region specific LCI databases are shown in Table 2.4. *ATHENA* is the most suitable for use in US and Canadian studies, as it contains the most comprehensive database of Canadian and US products and processes (Szalay 2007; Zacharia 2003). Eco-invent contain Swiss and European product and process data. As the databases are region specific, the outcomes of a study might be valid for that region only (Horvath 1997; Reap et al 2008; Szalay 2007). Hence, the choice of LCI database is a major decision to conduct any LCA study.

2.4.3.1 International LCA and LCI initiatives

In recent years, the European Commission (EC) carried out a project to develop the International Reference Life Cycle Data (ILCD) system. The overall goal is to provide an LCA information hub to access LCI data through a global LCA resources directory (ECJRC 2009a). This project developed a series of technical guidance documents (ILCD Handbook). The ILCD system allows users to export and import data free of cost to their customers (ECJRC 2009).

2.4.3.2 Australian LCA and LCI initiatives

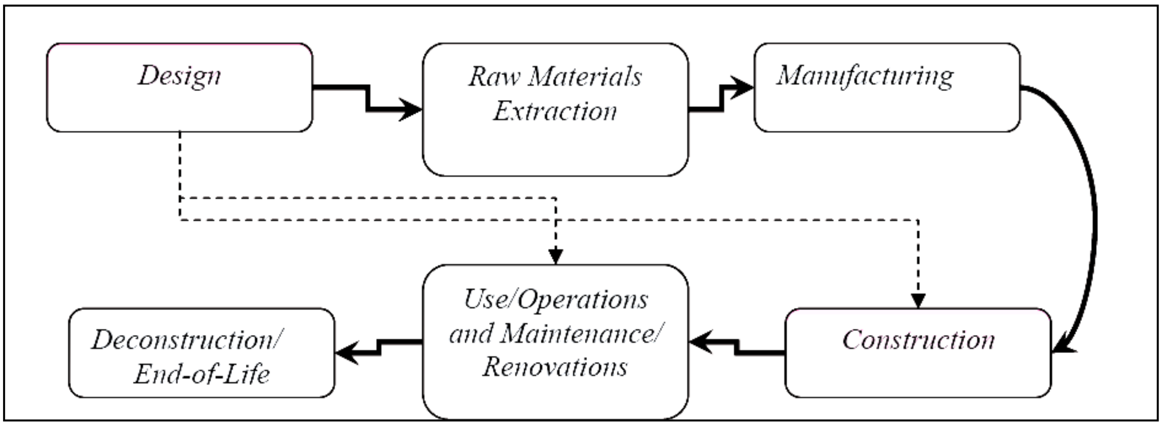
Over the last two decades, Europe, Canada and the USA were the leaders in developing LCA and LCI initiatives (Tharumaharajah & Grant 2006). An initiative to develop an Australian database followed in 1997. A series of stakeholder meetings were conducted in 2001 that recommended using *SimaPro* LCA software (Henriksen 2006). *SimaPro* now contains the Australian LCI database library.

The Australian Life Cycle Assessment Society (ALCAS) established its LCI group in 2002 (Newton et al 2009; Tharumaharajah & Grant 2006) and took up the challenge of establishing the Australian National Life Cycle Inventory Database Initiative (AusLCI). Aims of AusLCI are to provide a transparent, consistent and easily accessible and reliable national LCI database. All major industry, government and service organisations stakeholders have been involved in the development of the AusLCI database (Tharumaharajah & Grant 2006). AusLCI provides authoritative, comprehensive and transparent environmental information on a wide range of Australian products and services. The library of data are progressively updated (AusLCI 2009).

2.4.4 LCA of buildings

A typical life cycle of a building includes design, raw material extraction, processing, manufacturing, construction, use and maintenance, and finally end of life management (Bilec 2007), shown in Figure 2.13.

Figure 2.13: Life Cycle of a Building (Bilec 2007)



The raw material extraction to material production, heating and cooling, maintenance and end of life management of materials are the principal elements considered within the system boundary in an LCA study for buildings. Careful choice of these system boundaries is needed, as they may alter the outcome of the assessment significantly.

The key elements of some previous LCA studies are reviewed in the following discussion.

2.4.5 Review of contemporary LCA studies of residential buildings

In the following section, firstly, the assumptions of some key elements for previous studies are discussed, and secondly, the studies outcomes are discussed, with particular focus on the relevant aspects to this study.

2.4.5.1 The assumptions of some key elements for previous studies

There have been a number of LCA studies conducted on residential buildings in Australia and elsewhere.

Table 2.5 shows a summary of LCA studies conducted for residential buildings. The assumptions of some key elements are discussed in the following section.

Table 2.5: Summary of contemporary relevant LCA studies on residential buildings

Study		**Major Assumptions**		
		Life span	Functional unit	Impact category indicators
Australian	Iyer-Raniga & Wong (2012)	100 years	1 m^2 floor area	Carbon emission, energy, Photochemical oxidation, Eutrophications, Land use and Water use
	Carre (2011)	50 years	1 m^2 floor	GWP, CED, Water use, Solid waste, Photochemical oxidation, Eutrophications, Land use, and Resource depletion
	Rouwette (2010)	50 years	1 m^2 of wall	GHG and CED
European	Cuellar-Franca & Azapagic (2012)	50 years	total house	GWP, Acidification, Eutrophications, Abiotic depletion, Ozone depletion, Photochemical ozone creation, Human toxicity.
	Nemry et al (2010)	40 years	total house	GWP, Primary energy, Acidification, Eutrophications, Ozone depletion, Photochemical ozone creation
	Ortiz et al (2010)	50 years	1 m^2 floor	GWP, Acidification, Human toxicity, Abiotic depletion, Ozone depletion
	Szalay (2007)	50 years	total house	GWP, Acidification, Ozone depletion, Photochemical oxidation, Eutrophications
	Adalberth et al (2001)	50 years	usable floor area	GWP, Energy use, Acidification, Eutrophications, Photochemical ozone creation and Human toxicity
North American	Frenette et al (2010)	60 years	200 m^2 wall area	Human health, Ecosystem quality, Climate change and Resources use
	Kahhat et al (2009)	50 years	200 m^2 wall area	GWP, Primary energy, Solid waste, Air/Water pollution, and Weighted resources
	Lippike et al (2004)	75 years	total house	GWP, Embodied energy, Solid waste, Air and Water pollution emission
	Blanchard & Reppe (1998)	50 years	total house	GWP, Primary energy

Building lifespan assumptions vary significantly among previous LCA studies of buildings. There is no consensus to standardise the lifespan of buildings (Cuellar-Franca & Azapagic 2012; Carre 2011).

Table 2.5 shows that building lifespan assumptions ranged from 40 to 100 years, and the median value is 50 years. This assumption significantly affects the proportion of impacts in the various lifecycle stages. A recent Australian study reported that the life cycle primary energy and GHG emissions could be reduced by nearly 50% when building lifetime was reduced from 100 years to 50 years (Iyer-Raniga & Wong 2012).

Most LCA studies are undertaken using ISO 14044 standards, which define the functional as a unit of comparison. The most common functional unit for residential building studies is ‘1 square meter’ or ‘total house’ (Table 2.5). This is a good basis for comparison, as the functional unit is comparable to those of other systems serving the same functions (ARUP 2006; Carre 2011; Roy et al 2009). For example, comparing two doors made from different materials are meaningful if the same door installed at the same location (ARUP 2006). In addition to floor area, a time frame for usage could be included (ARUP 2006; Carre 2011). The total house is useful only, if the houses to be compared have similar floor space (Carre 2011).

The typologies of building vary widely from region to region, as discussed in Section 2.2. The reason may be that the assemblage designs must comply with regional standards and guidelines (BCA 2005; QUT 2011). The key variations are single or double storey heritage or modern and homes with star rating designs, so the typologies of buildings need to consider when compare the study outcomes. There is also some variation in floor, wall and roof assemblages due to compliance (BCA 2005; QUT 2011). For example, some studies consider a concrete slab floor and some a suspended timber floor.

The geographic location has a significant effect on study outcomes. The major influence is that the heating and cooling needs depend on the particular geographical location of that particular study (Carre 2011; Kahhat et al 2009). For example, Carre (2011) reported that North American and Australian dwellings consumed higher emissions per unit of energy during the operation life phase compared with European dwellings although this may be affected by both climate and the difference in building practices. Climate influence also varies within a large continent like Australia. Carre (2011) reported wide variations in GHG impacts in different cities: the operation phases contributed 57-72% in Brisbane, 76-86% in Melbourne and 60-70% in Sydney, which means the Melbourne climate requires the highest operational energy.

Choice of system boundary has a significant impact on a study’s outcomes. Some studies include comprehensive life cycle phases associated with construction, use/operation, maintenance and end of life (Carre 2011; Cuellar-Franca & Azapagic 2012; Iyer-Raniga & Wong 2012). Others excluded some life cycle phases. For example, Rouwette (2010) included some maintenance but excluded part of major renovation for maintenance, and recycling/land filling for disposal. Hence, Rouwette's study has limited comparability to Carre and Iyer-Raniga & Wong, even though they use the same region specific data.

Many LCA software packages and region specific life cycle inventory databases have been used in previous studies. While any LCA software can be used was valid, the preference in recent studies is to use region specific LCI data. For example, several recent Australian LCA studies were conducted using *SimaPro* software and region specific data (Carre 2011; Iyer-Raniga & Wong 2012; Rouwette 2010). One UK study was conducted using *GaBi* software and region specific data (Cuellar-Franca & Azapagic 2012). Two recent North American studies were conducted using *ATHENA* software and North American region specific data (Frenette et al 2010; Kahhat et al 2009). While the outcomes of these studies are valid for their region, the limitation is that they are not comparable to studies done in other regions. Hence, the choice of LCI database is a major decision in any LCA study.

A wide range of assumptions must be made in any LCA study, which affects the results significantly. Some studies consider space heating and cooling effects only (Carre 2011; Iyer-Raniga & Wong 2012; Rouwette 2010). Others consider space heating and cooling as well as water heating, lighting, and cooking (Cuellar-Franca & Azapagic 2012; Blanchard & Reppe 1998; Maddox & Nunn 2003; Ortiz et al 2010). Between these two sets of studies, there are significantly different results for example, the ratio of GHG emission in construction to operation phase ranges from 1:1 to 1:5 for the first set of studies, and up to 1:8 for the second set of studies. The greater variability in the second set may be partly attributed to the differences in model assumptions: inclusion of water heating, lighting and household appliances efficiency beyond heating and cooling, would increase the relative contribution of operation energy (Carre 2011).

The assumptions about appliances efficiency for heating and cooling vary among the recent Australian studies. For example, for heating efficiency, Carre (2011) assumed 70% thermal efficiency for a natural gas fitted heating system; Morrissey & Horne (2011) assumed a 52.5% efficiency for a ducted heating system (based on 75% efficiency and 30% duct losses); Iyer-Raniga & Wong (2012) assumed a 65% efficiency for a central gas heating system excluding ducted losses. Similarly, for cooling, Carre (2011) modelled an electric refrigerative cooling system with coefficient of performance (COP) of 3.5 and 20% duct loss; Morrissey & Horne (2011) modelled a ducted cooling system with a COP of 1.96 (2.79 COP and 30% duct losses); Iyer-Raniga & Wong (2012) modelled minimum energy performance standard appliance efficiencies and COP of 3. On the other hand, Rouwette (2010) did not specify the appliances efficiency.

The assumptions about the timings of renovations also vary widely. The replacement frequency varies from high to low depending on the material and region (Mithraratne 2001; Oswald 2003; Szalay 2007). For example, weatherboard may need to be replaced more often than more durable claddings, ranging from 25 to 50 years (Oswald 2003). Similarly, minor renovation for painting may need more frequently 6 to 25 years (Oswald 2003). Carre (2011) considered minor renovation for painting at every 10 years interval and major renovation for weatherboard at 50 years. Some studies exclude parts of renovation or do not specify the details of what is included (Cuellar-Franca & Azapagic 2012; Rouwette 2010). Therefore, there is a further limitation on comparability among studies.

Assumptions about disposal also vary among recent Australian studies. Iyer-Raniga & Wong (2012) assumed all the material was disposed to landfill with no carbon sequestration benefit. Carre (2011) modelled dismantling, transportation and partial recycling as well as land filling, and assumed carbon sequestration benefits. Rouwette (2010) modelled only transportation for the disposal of waste from construction for both recycling and land fill. This is another limitation on comparability among these studies.

In terms of impact analysis, the choice of environmental indicators varies from study to study. GHG and CED are indicators most often selected because it is the greatest environmental challenge facing the built environment (Ortiz et al 2010) Blanchard & Reppe 1998), or because the scope was limited by client (Rouwette 2010). Recent Australian studies also look at land use, water use, photochemical oxidation and eutrophications (Carre 2011; Iyer-Raniga & Wong 2012). The selection depends on specific goals for each particular study.

The wide range of choices and assumptions are described in this section. These have significant effects on outcomes. For example, Carre reported that the construction phase contributed 14-45% to GHG emission whilst Rouwette (2010) and Maddox & Nunn (2003) reported 49% and 3-5% respectively. Hence, when comparisons between studies are made, due regard for assumption must be given.

The key outcomes for previous studies are discussed in the next section.

2.4.5.2 *The variation of the key outcomes for previous LCA studies*

In this section, firstly, the comparisons with the results of recent Australian LCA studies of residential buildings are discussed. Secondly, comparison with the results of the European and North American LCA studies is made.

Table 2.6: LCA results comparison among Australian residential buildings

Study	System description and assumptions	GHG	CED
Carre (2011)	Australian climate (Brisbane, Sydney, and Melbourne), 5 star rating, 50-year lifetime; excludes interior decorations and household appliances; assumes a COP of 3.5 with 20% ducting loss for cooling, 70% efficiency for heating; disposal phase includes dismantling of the original construction materials and their transport to recycling and land fill	• construction 31–43% • operation 53-68% • maintenance 4-6% • disposal -1 to -5%	• construction 31–44% • operation 52–64% • maintenance 5-6% • disposal (-1 to -3%)
Rouwette (2010)	Australian climate (Newcastle, Melbourne and Brisbane), 50-years lifetime; excludes interior decorations and household appliances and major renovation; star rating and appliances energy efficiency not specified; disposal phase includes only transportation impact for construction materials to recycling and land filling.	(Newcastle climate) • construction 47% • operation 51% • disposal (2%)	-not specified
Iyer-Raniga & Wong (2012)	Australian climate (Victoria), various 0.8 to 5.1 star rating, 100-year lifetimes; excludes interior decorations and household appliances; includes appliances efficiency for operational energy; assumes 65% appliances efficiency for heating and a COP of 3 and no duct losses for cooling; disposal phase includes dismantling of all the materials to landfill, with no carbon sequestration or material energy recovery from land fill	• Construction, maintenance and disposal ranged 7-24% • operation 76-93%	• Construction, maintenance and disposal 4-18% • operation 82-96%
Maddox & Nunn (2003)	Australian climate, 60-year lifetime; includes interior decorations, heating/cooling, lighting and household appliances; excludes major renovations, the appliances efficiency not specified	• construction 3-5% • operations 90%	-

For both GHG and CED, LCA results of Australian studies are summarised in Table 2.6 reported the contributions among life stages. There is a high degree of dissimilarities for both GHG and CED: these differences may be attributed to the variation in system description and assumptions.

Iyer-Raniga & Wong (2012) and Maddox & Nunn (2003) found that the operation phase contributed more than 90% of GHG emissions. Their study gave a ratio of construction to operation phase contributions of 1:10 to 1:18. The other studies Rouwette (2010) and Carre (2011) have a range of ratios of construction to operation of 1:1 to 1:5. This large difference is not surprising, but is attributed to the differences in model assumptions (Table 2.6): longer building lifetime and inclusion of water heating, lighting and household appliances efficiency and COP, would increase the relative contribution of operation energy. Hence, operational energy would make a bigger contribution in their model than Carre's and Rouwette's study, and so construction would be proportionally smaller.

The findings by Rouwette (2010) are not similar to Carre's (2011) study. The differences may be attributed to differences in assumptions (such as maintenance and carbon sequestration in disposal). Hence, Rouwette did not report any GHG emission for material replacement as maintenance. Rouwette (2010) also excluded demolition due to the scarcity of reliable data on demolition process. Rouwette included only transportation impact for the operation of a landfill site, but Carre's study included maintenance, transportation and landfill as well as reuse and recycling impact for disposal.

LCA results among European and North American studies are summarised in Table 2.7 among life stages. For both GHG and CED, the degree of variation for life cycle phase is not high, except Szalay's study. Szalay looked the maintenance impact separately while other studies incorporated it to operation/use phase. Hence, the other little differences may be attributed to the variation in system description and assumptions.

Table 2.7: Results comparison with other LCA studies of residential housings

Study	System description and assumptions	GHG	CED
Cuellar-Franca, & Azapagic (2012)	UK residential house, 50-year lifetime; includes heating/cooling, water heating, cocking, lighting, and appliances energy consumption; assumes reuse, recycling and landfill for waste treatment; energy ratings and appliances energy efficiency not specified	• construction 9% • operation/use 90% • disposal 1%	-not specified
Ortiz et al (2010)	Spanish and Columbian house, 50-year lifetime; includes space heating/cooling, water heating, cocking, lighting, and appliances energy consumption; assumes a COP of 2.35 for heating and 1.85 for cooling; disposal phase includes dismantling of materials and their transport to the land fill	• construction 8-28% • operation/use 69-91% • disposal 1-3%	-not specified
Szalay (2007)	Hungarian residential house, 50-year lifetime; includes heating and cooling, hot water, lighting; excludes interior decorations; using tabulated values for gross operation energy; disposal phase includes recycling (50%) as well as their transportation.	• construction 14-21% • operation 67-72% • maintenance 7-11% • disposal 3-5%	• construction 14-20% • operation 68-77% • maintenance 6-13% disposal 1-2%
Blanchard & Reppe (1998)	United States residential house, 50-year lifetime; includes heating/cooling, lighting, decorations and household appliances; excludes major renovation, recycling, incineration; energy ratings and appliances efficiency not specified	• construction 8-21%% • operation/use 78-92% • disposal 1-2%	• construction 6-16% • operation/use 83-94% • disposal less than 1%

The findings for the water usages appear in two recent Australian studies in residential house design (Carre 2011; Iyer-Raniga & Wong 2012). Both the studies, the authors had found an interpretation challenge how the actual water was quantified. Carre found construction and maintenance phase dominate the total water usage, 72% and 36%, respectively. Carre (2011) also found operation and disposal have less water use.

The findings for the solid waste also appear in few studies (Carre 2011; Kahhat et al 2009; Lippike et al 2004), but focus on building elemental aspect. Carre (2011) looked at the difference between elevated timber floor and concrete slab construction, and found 20-30% difference of the effect of solid waste. Kahhat et al (2009) found 5% variation of the effect of solid waste between the concrete block and insulated concrete wall designs. Lippike et al (2004) found 9% difference of the effects of solid waste between the steel and wood frame residential house. This variation may be attributed for the assumptions of disposal. For example, Carre's study considered both reuse/recycling as well as landfill for waste disposal, while Lippike et al (2004) summarised the weight of all waste materials.

In summary, LCA studies are generally undertaken using ISO 14044 standards. While the choice of LCA software does not appear to affect outcomes, the LCI database is region specific, so the database relevant to the study's region should be used. There is wide variation in choice of building lifespan, but the median is 50 years. The outcomes of a study depend on choice of building typology and construction material as well as assumptions made about energy efficiency appliances used in the particular house. The assumptions about the system boundaries also have a major impact such as whether water heating, lighting and cooking is included. LCA studies on residential building focus on a limited range of environmental impacts, most commonly GHG and CED. Choice of impact indicators depends on the study focus.

The key elements of some previous LCC studies on buildings are reviewed in the following discussion.

2.5 LIFE CYCLE COST APPROACH OF BUILDINGS

2.5.1 Overview of costing techniques of buildings

Life cycle costing (LCC) is a technique to determine the sum of all expenses associated with a product or project including acquisition, installation, operation, maintenance, refurbishment, discarding, and disposal costs (Standards Australia 1999). Life-Cycle Cost-Benefit (LCCB) analysis and Cost Benefit Analysis (CBA) are similar approaches to LCC that assess the viability of investments, to identify the highest net benefit (Winkler et al 2002). LCCB and CBA include user costs/benefits analysis such as benefits to road users when a new bridge is built to reduce traffic congestion (Thoft-Christensen 2010). Evaluating an investment in environmentally sound building is no different from evaluating any other type of capital project (Davis & Horvei 1995). Several studies on residential housing in Australia describe their approach as LCCB (Moore & Morrisey 2010; Moore, Morrisey & Horn 2010; Morrisey & Horne 2011) because they include future savings in energy costs due to investment in higher star rating building. The traditional LCC model for buildings consists of total investment cost, annual operation and maintenance cost, and salvage and disposal cost (Levander et al 2009; Sterner 2002), hence energy saving are included in standard LCC, hence LCC is a suitable tool for studies on residential housing design optimisation.

There are several standards to guide LCC analysis. The standard organisations that have developed these include ISO, Australian Standards, New Zealand Standards and the American Society for Testing and Materials (ASTM). Standards Australia developed a standard for life cycle costing, AS-4536 (Standards Australia 1999).

2.5.2 Methodological review of LCC approach in buildings

The initial and future expenses are combined in LCC analysis in buildings. For future expenses, LCC must take into account the time value of money (Fabrycky & Blanchard 1991; Fuller & Petersen 1996; ISO 2008). This is because money has time value: if it set aside today that would increase every year by the net inflation and interest rate (Bakis et al 2003).

There are several ways to estimate the future costs of building related activities. Future costs are discounted to their present value using a suitable rate over their lifetime (Fuller & Petersen 1996; Glucha & Baumann 2004; Kneifel 2010; Leckner & Zmeureanu 2011; Schade 2007; Snodgrass 2008). This means that the discounted costs represent the total amount that has to be reserved today to finance the expenses in future (Mithraratne & Vale 2004a; Sterner 2002).

Future costs are estimated based on the current price inflated with an estimate of future inflation then discounted to present value (Glick & Guggemos 2010; Sterner 2002). The discount rate is the investment "premium" over and above inflation (DLMC 2007). Inflation is the general increase of prices over time, without corresponding increase in value (Sterner 2002). Other authors also suggest that LCC methods should include inflation in calculations (Fabrycky & Blanchard 1991; Korpi & Ala-Risku 2008).

In terms of accuracy, LCC of buildings contain several uncertainties. Buildings have long lifetimes. The longer the time considered, the less accurate the forecast of inflation and discount rates (Bakis et al 2003; Glick & Guggemos 2010; Sterner 2002). Accuracy is also affected by the commercial nature of prices (Morrissey & Horne 2011). For example, property values vary depending on their commercial value (Bakis et al 2003). Additionally, different product prices usually increase at different rates over time (Sterner 2002). Therefore, the estimated LCC may be substantially different to the actual future cost (Glucha & Baumann 2004).

To improve the accuracy, the choice of appropriate discount and inflation rate are critical (Korpi & Ala-Risku 2008; Sterner 2002). The discount rate decreases the effect of uncertainty for future consequences (Glucha & Baumann 2004; Sterner 2002). Therefore, several authors suggest a sensitivity analysis to estimate the effects of these uncertainties (Sterner 2002; Zacharia 2003).

Davis Langdon Management Consulting (DLMC) reports that LCC analyses often exclude inflation effects (DLMC 2007). Glucha & Baumann (2004) point out that if real costs are used, the discount rate should not include inflation. Robinson (1986) used a real cost approach: current costs are used for initial and recurring costs, and no allowances are made for inflation (DLMC 2007).

2.5.3 LCC in buildings

LCC in buildings are conducted for various reasons. Several authors report that LCC mainly informs the designers and clients about the different investment scenarios (Glick & Guggemos 2010; Moore, Morrissey & Horne 2010; Morrissey & Horne 2011; Sterner 2002). LCC of buildings may also be applied for housing energy efficiency measures (Belusko & O'Leary 2010; Moore, Morrissey & Horne 2010; Morrissey & Horne 2011). Some authors argued that LCC identifies the best design options of construction (Bakis et al 2003). Some authors reported that LCC is used as a design support tool for decision-making (Korpi & Ala-Risku 2008; Mithraratne & Vale 2004a).

In the following discussion, the key elements of some previous studies of cost analyses of buildings are discussed, with particular focus on aspects relevance to this study.

2.5.4 Review of contemporary cost analysis of buildings

There have been many costing studies on buildings reported in the literature. Table 2.8 shows a summary of some studies for residential buildings. In this section, the key elements of previous studies relevant to this study are discussed. The assumptions made, and how these affect the study outcomes, are also discussed.

Table 2.8: Summary of relevant cost analyses of residential buildings

Study		Major assumption and findings
Australian	Morrissey & Horne (2010)	The study applied a thermal modelling approach within an LCC framework for dwelling Discount rate: 3.5% over 0-30 years; 3% over 30-70 years Findings: the energy efficient building design is the most cost-effective Limitations: Only operation costs are reported; Cost contributions from the life cycle stages are not specified
	McLeod & Fay (2010)	The study examines the cost effectiveness of thermal performance measures Discount rate: not specified as only construction costs are considered Findings: The construction cost is approximately $150,000 for a 4 star rating house. The average cost per star rating improvement is (around $3000) Limitations: Only construction costs are included. Whole life cycle costs are neglected
	Belusko & O'Leary (2010)	The study estimates retrofit cost to achieve a 6 star rating from existing residential houses Discount rate: not specified as only construction costs are considered Findings: An increase in construction costs of 1-2% achieve an increase from 4.9 to 6 stars The average cost per star rating was $3415 +/-46% Limitations: construction and life cycle costs are not specified. Average house and land package are specified only
European	Sterner (2002)	The study estimated LCC of residential dwellings Discount rate: 4% over 50 years Findings: The construction, operating and maintenance costs are about 56%, 22% and 2%,respectively Limitations: disposal costs are not specified
	Johansson & Oberg (2001)	This study estimated LCC of multifamily dwellings including periodic maintenance Discount rate: 2.5% over 60 years Findings: operation and maintenance costs are 23-34% and 13-20%, respectively Limitations: Construction costs are not included.
	Bejrum et al (1986)	This study estimated LCC of dwelling, including construction, operation and maintenance Discount rate: 4% over 50 years Findings: construction, operation and maintenance costs are 65%, 25% and 10%, respectively Limitations: disposal costs are not estimated separately

North American	Zacharia (2003)	This study estimates the total present value of buildings, including construction, operation and disposal costs Discount rate: 2, 4, 6, 8 % over 35 years Findings: Average construction, operation and disposal cost are 88%, 11% and 2%, respectively This LCC model is sensitive to discount rate. Limitations: Maintenance cost is not included
	Blanchard & Reppe (1998)	This study estimates LCC of residential buildings, including accumulated mortgage (land and construction), operational energy and maintenance/improvement costs Discount rate: 4% over 50 years Findings: mortgage and operation contributed 68-79% and 3-9%, respectively Limitations: disposal cost are not included

There have been many costing studies on residential buildings in Australia. These had several different goals. Morrissey & Horne (2011) applied thermal modelling to investigate LCC; McLeod & Fay (2011) estimated the effect on capital cost and construction techniques of increases in thermal performance; Belusko & O'Leary (2010) investigated the cost required to achieve 6 star rating designs. The main limitation of these studies is that none considered whole building and life cycle costs.

A wide range of life times were considered, from 35 to 70 years. Several authors used the median of 50 years' time horizon (Bejrum et al 1986; Blanchard & Reppe 1998; Sterner 2002).

The discount rate varied from 2% to 8% with a median of 4% (Bejrum et al 1986; Blanchard & Reppe 1998; Sterner 2002; Zacharia 2003). Some authors used more than one discount rate. For example, Morrissey & Horne (2011) used a 3.5% discount rate for 0-30 year, and 3% for 30-70 years, in line with UK Government practice. Zacharia (2003) analysed the effect of discount rate on LCC, applying a range from 2 to 8%.

The studies outcomes depended on assumptions about the system boundaries. This is shown clearly in the relative contribution of the life stages for construction, operation, maintenance and disposal. Table 2.8 shows that the construction (initial phase) has the highest contribution of all life phases to LCC. This varied widely from 56 to 88% (Bejrum et al 1986; Blanchard & Reppe 1998; Sterner 2002; Zacharia 2003).

In conclusion, the study outcomes depend significantly on assumptions such as discount rate, lifetime and systems boundary. The construction life stage contributes the most to LCC but operation, maintenance and disposal are also significant.

2.6 OPTIMISATION OF BUILDING DESIGN

2.6.1 Optimisation: a general overview

Optimisation is a process of finding the best solution to a problem that simultaneously meets all imposed constraints (Khajehpour 2001; Musch 2008). Wang (2005) pointed that optimisation aims at finding the best way to use resources, while at the same time not violating any of the constraints.

In the following discussion, the key elements of a number of previous optimisation studies are discussed, focussing on aspects of particularly relevance to this study. How the approach affects the study outcomes is also described.

2.6.2 Review of optimisation studies in buildings

A number of optimisation studies have been conducted on buildings. Table 2.9 shows a summary of a selection of studies of buildings that considered optimisation using mathematical modelling of economic and environmental impacts.

Table 2.9: Summary of contemporary optimisation studies of buildings

Study		Objective	Techniques	Major focus and assumptions
European	Asadi et al (2012)	Minimise retrofit costs and maximise energy savings	Tchebycheff Programming using MOO	Focuses on building retrofit measures Uses linear/non linear mathematical model in MATLAB Uses a trade-off relationship Applied to whole building but not whole life cycle Minimises energy use cost effectively
	Diakaki et al (2008)	Minimise energy requirements	Goal programming using MOO	Optimises energy efficiency measures Uses LINGO software with a weighted approach Uses a trade-off relationship Applies to whole building but not whole life cycle
Asia pacific	Ren et al (2010)	Minimise energy cost and environmental impact	Linear Programming using MOO	Focuses on to analyse the optimal operating strategy Uses LINGO software with a weighted approach Uses a trade-off relationship Applies to whole building but not whole life cycle
North American	Wang (2005)	Life cycle cost and environmental impact	Genetic Algorithm using SOO and MOO	Optimises building orientation, shape and design Uses simulation based program GBOptimizer Uses a trade-off relationship Applies to whole building and whole life cycle
	Castro-Lacouture et al (2009)	Life cycle cost and environmental impact	Mixed Integer using MOO	Optimises selected building materials Uses mixed integer mathematical model Uses a trade-off relationship Does not include whole building nor whole life cycle
	Zacharia (2003)	Minimising life cycle cost and environmental impact	Linear Programming using SOO	Focuses on optimisation of building design Uses LINDO software but neglects weighting Uses a trade-off relationship Applies to whole building and whole life cycle

A number of studies applied optimisation to building orientation, shape and design perspective (Khajehpour 2001; Wang 2005). Others optimised building materials (Asadi et al 2012; Castro-Lacouture et al 2009; Zacharia 2003). Some studies optimised the whole building within a whole life cycle perspective (Wang 2005; Zacharia 2003) while others optimised building retrofit measures using energy efficiency (Asadi et al 2012; Castro-Lacouture et al 2009; Diakaki et al 2008) without considering the whole building or life cycle.

Several optimisation studies focussed on minimising economic and environmental objective functions (Wang 2005; Zacharia 2003). Others focussed on minimising environment impacts and maximising performances from a building or building material perspective (Musch 2008). A few studies optimised building materials within a building life cycle context (Wang 2005; Zacharia 2003). The optimisation of residential building by varying materials assemblages in whole building life cycle context is very limited (Wang 2005; Zacharia 2003). In these contexts, there are no Australian studies reported in the literature.

A variety of software is used in optimisation studies. EXCEL is used to show a comparison between two or more data sets. MATLAB is widely used for standard and large-scale optimisation (The MathWorks 2011). LINDO and LINGO from LINDO Systems is widely used for mathematical optimisation (LINDO Systems 2012).

Many different optimisations techniques have been used in building studies in the literature (Table 2.9). Several studies applied a ‘single-objective’ (SOO) optimisation approach (Wang 2005; Zacharia 2003), while others applied multi-objective (MOO) optimisation (Asadi et al 2012; Castro-Lacouture et al 2009; Diakaki et al 2008; Ren et al 2010).

The next two sections briefly review the literature on software and methodological approach to model SOO and MOO.

2.6.3 Optimisation software: methodological review

A variety of software is used in optimisation studies of residential buildings, including EXCEL, MATLAB, LINDO and LINGO.

EXCEL has been used in some studies for simple cases to show a comparison between two (or more) data sets (Carre 2011; Rouwette 2010) but optimisation of design considering both LCA and LCC was beyond the scope of these studies.

MATLAB has an optimisation toolbox for mathematical programming. It includes functions for linear, quadratic, binary integer programming, nonlinear optimisation and multi-objective optimisation (The MathWorks 2011). It is widely used for standard and large-scale optimisation. It has been used in some studies on residential housing (Asadi et al 2012; Hani & Koiv 2012) but optimisation of assemblage design considering both LCA and LCC was beyond the scope of these studies.

LINDO Systems is a leader in mathematical optimisation. It provides fast, easy to use tools (LINDO Systems 2012). LINDO minimises or maximises the objective functions subject to a set of constraints using linear or quadratic or and integer programming (Khan & Ardil 2009; Khan & Min-Allah 2011; Zacharia 2003). The constraints may be linear equalities or inequalities. LINDO can treat the problem as an integer-programming problem, if all variables can be realistically represented as non-negative integers. LINDO has been used in relatively few optimisation studies on residential buildings. Zacharia (2003) considered both LCA and LCC in his optimisation study of a typical Canadian residential dwelling.

LINGO is another optimiser from LINDO Systems with a set of solvers for linear, integer, and nonlinear models used in studies by Diakaki et al (2008) and Ren et al (2010). LINGO is a more advanced and comprehensive tool than LINDO, which is useful with larger models (LINDO Systems 2012; Zacharia 2003).

2.6.4 Optimisations techniques: methodological overview

In SOO, a single objective function is maximised or minimised to find the optimum (Asadi et al 2012; Wang 2005; Zacharia 2003). For example, the objective function might be to minimise cost or environmental impact or maximise performance with better assemblage design for buildings. In SOO, the value of the optimum for any particular objective function depends on whether the other objective functions are maximised or minimised (Wang 2005; Zacharia 2003). The optimum depends on which objective function is considered. However, taking a SOO approach is ineffective, when multiple objective functions must be optimised at the same time. If multiple criteria must be optimised simultaneously, MOO must be used.

In MOO, more than one objective functions at a time is maximised or minimised (Kolokotsa et al 2009; Shuqing 2005; Wang 2005). Cost and environmental impact are optimised in a two objective MOO approach in several studies (Wang 2005; Zacharia 2003). Some studies optimised three objective functions: Azapagic & Clift (1999) optimised production, cost and environmental impacts while Khajehpour (2001) optimised capital cost, operating cost and annual income revenue.

A popular approach to MOO is a weighted–sum approach (Hawe & Sykulski 2008; Shuqing 2005). In this approach, the MOO is converted to a SOO problem. A weight is assigned to each normalised objective function so that the problem is converted into a single objective problem with a scalar objective function. This approach was adopted in several previous optimisation studies (Diakaki et al 2008; Hawe & Sykulski 2008; Konak et al 2006; Shuqing 2005). Normalised data are used in these approaches so that the categories with different units can be compared on the same scale. Normalised data can be calculated using the actual value divided by the optimum value (Azapagic & Clift 1999).

There is no particular rule to select the weighting for the objective functions (Shuqing 2005). Appropriate weightings are difficult to choose for a problem with a number of objective functions. Weightings may be determined arbitrarily by the decision maker or by a simple trial and error method (Shuqing 2005). A random weighting is commonly applied approach to generate a set of solutions (Murata et al 1996; Murata et al 2001; Shuqing 2005).

In MOO, the outcome is not usually a single solution. MOO provides a set of optimal solutions, depending on the objective functions (Alarcon-Rodriguez et al 2010; Azapagic & Clift 1999; Kolokotsa 2009). Several authors pointed out that contradictory objective functions are often minimised or maximised in optimisation, particularly in MOO (Alarcon-Rodriguez et al 2010; Ren et al 2010). It is a particular challenge to minimise or maximise contradictory objective functions simultaneously (Ren et al 2010; Wang 2005). To deal with such difficult problems, some authors used a trade-off between the objective functions (Alarcon-Rodriguez et al 2010; Azapagic & Clift 1999; Tan 2005; Wang 2005; Zacharia 2003).

Trade-off refers to optimising none but pushing all as close to their optimum (Ashby 2000; Azapagic & Clift 1999; Zacharia 2003). This often is the case for building due to the complicated interactions among parameters (Ashby 2000; Wang 2005; Zacharia 2003). The trade-off between different metric performances (i.e. cost, mechanical, or environmental effects) is difficult. Optimising only one metric often makes another metric worse (Ashby 2000; Azapagic & Clift 1999; Tan 2005; Zacharia 2003). Several authors have used trade-off solutions as a way of visualising alternative compromises, where the decision maker can select an optimal solution from a range of optimal alternatives (Ashby 2000; Azapagic 1999; Tan 2005). Hence, the best are identified as close to their best favourable.

A wide range of programming techniques is available to solve optimisation problems. Several different MOO techniques have been used in previous optimisation studies in buildings, shown in Figure 2.9. The programming technique depends on the problem size and complexity as well as on the decision-making context (Azapagic & Clift 1999; Khan & Ardil 2009; Khan & Min-Allah 2011; Zacharia 2003).

Several authors point out that the accuracy of optimisation depends on the optimisation model and product design techniques (Azapagic & Clift 1999; Wang 2005). It also depends on variables, constraints, the optimisation algorithm, objective functions as well as simulation techniques (Wang 2005).

In summary, a wide range of objective functions and variables are considered, when optimising a building. Several studies optimised building orientation and materials but optimisation of building elements (floors, walls and roofing) in a whole life cycle context is still limited. Some studies focused on optimisation of costs, mechanical, and environmental aspects of materials or retrofits, without taking a whole building life perspective. Several studies adopted SOO approach while others adopted MOO approach. The most popular approach to MOO is a weighted–sum approach using normalised objective functions, where the MOO is converted to a SOO problem with a scalar objective function. Contradictory objective functions are often found in optimisation studies, particularly in MOO. The best choices are a compromise or trade-off.

2.7 SUMMARY OF LITERATURE REVIEW AND RESEARCH GAP

This chapter reviews the key relevant literature regarding building typology, building energy rating, and thermal properties of material, affecting the environmental and economic impact of building. It also discusses the relevant literature regarding LCA, LCC as well as optimisation relevant to buildings. Furthermore, it identified the following major points and research gap:

- The typologies of building vary due to variation in assembly design of building systems, standards and government policies. For example, the level of thermal performances for new residential building is now regulated as 6 stars.

- Building assembly designs use a range of energy intensive processes from material extraction to final disposal. Embodied energy depends on production, processing, use as well as end of life management of buildings. The contribution of space heating and cooling during operation has the most significant impact. The impact varies with construction type, location and energy efficiency performance of the materials. Numerous studies have shown that thermal performance of building components can be improved, for example, by adding insulation. Some studies have reported that the effect of changing material on environmental impact may be positive or negative over the building life cycle. Hence, the materials used in a building design should be compared based on thermal performance of the assembly over the whole life cycle rather than just inherent material properties. However, only a few studies have taken this approach.

- LCA aims to evaluate the relative impact of life cycle stages depend on what is included within the system boundary. Functional unit, life cycle inventory and assumptions vary markedly among LCA studies of residential buildings. The building typology, regulation, climate, building life span and inclusion of major renovations also vary. These affect the study outcomes. Outcomes of a study are generally valid for that particular region only for that building type and that life span. The selection of impact category indicators depends on the study focus. GHG and CED are most common. However, only a few studies have been undertaken on Australian dwellings. Hence, an LCA study of a residential dwelling built to Australian regulations, climate, and life span, and using a whole life cycle approach with a broader system boundary, is an important contribution to the literature.

- All initial and future costs are combined in an LCC analysis. To equate them with present value, a discount rate is applied to future costs. Inflation is applied to current costs to estimate the general increase of prices of goods and services over time. Outcomes for life cycle stages vary depending on assumptions such as discount rate and lifetime. The construction life stage contributes most to LCC but operation, maintenance and disposal are not negligible. Several discounting rates may provide an option to qualify the outcome. However, very few LCC studies have been undertaken on Australian residential dwellings using a whole of life cycle approach. Hence, an LCC study of an Australian residential dwelling is an important contribution to the literature.

- A range of objective functions and variables are considered in optimisation of buildings. Optimisation studies generally focus on building orientation and materials context. A range of methods for optimisation is used. The approach depends on the complexity of the problem and on the decision-making context. Contradictory objective functions are often found in multi-objective problems, hence a compromise or trade-off solution is needed. However, few studies have considered optimisation of building elements design (floor, wall and roof) in a whole life cycle context.

Hence there is a major research gap, as summarised above: there are no published studies that have taken a whole life cycle approach to both LCA and LCC for an Australian residential building, using optimization of building element design.

Therefore, this study posed the following research questions:

1. What is the effect on the whole life cycle environmental and economic impact of a residential building of varying materials in the wall, roof and floor assemblage designs?
2. Which optimisation approach is the most useful for comparing these effects?

The tools and techniques used in this study are described in the next chapter. It discusses how to model LCA and LCC of a residential building. It also discusses how to model single or multi-objective optimisation.

CHAPTER 3: RESEARCH METHODOLOGY

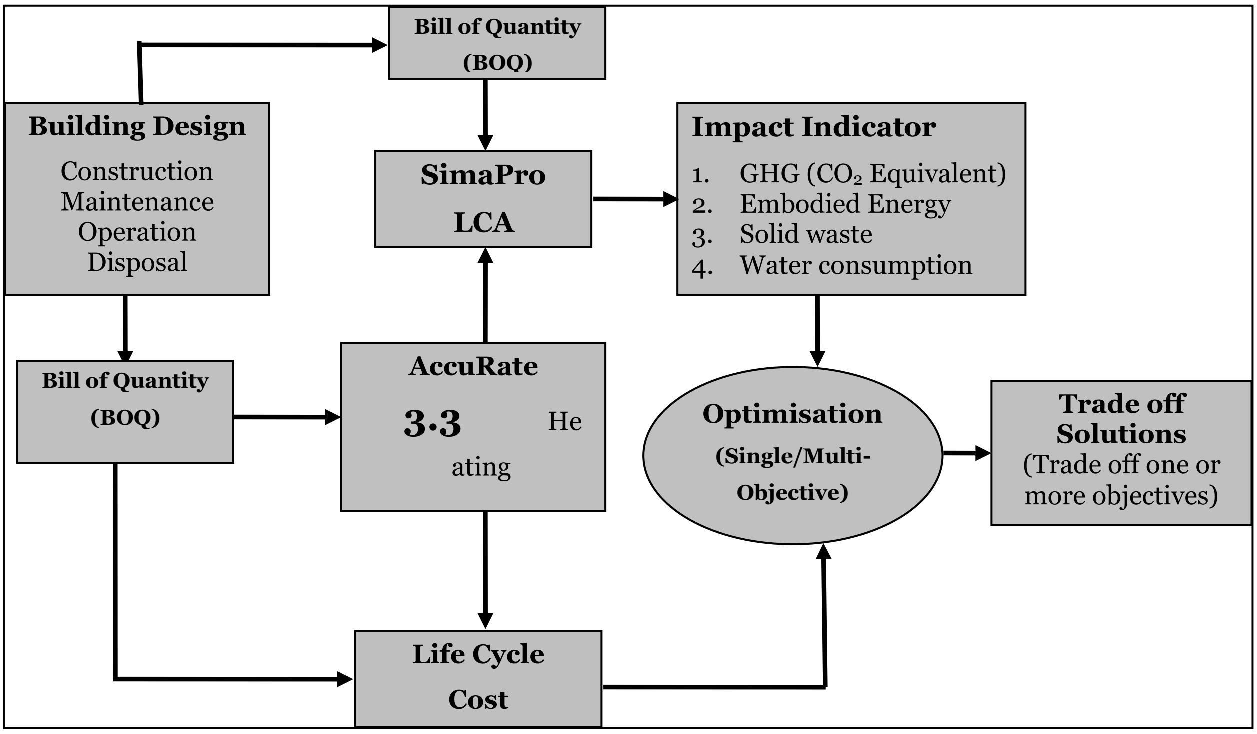
Introduction; Methodological framework of this study; Case selection and modelling step; Approach of modelling step; critiques of modelling tools; Summary

3.1 INTRODUCTION

This chapter describes the methodology to undertake this research. It discusses how to undertake life cycle assessment (LCA) and life cycle costing (LCC) of a residential building. It also discusses how to undertake single or multi-objective optimisation. Finally, the software tools and methods used in this study are critiqued.

3.2 METHODOLOGICAL FRAMEWORK OF THIS STUDY

Figure 3.1: Methodological framework



The methodological framework encompasses both environmental and economic optimisation of material usage in residential house design. Figure 3.1 shows the framework used in this study. The environmental impacts were modelled using *SimaPro* software. The operational energy requirements were modelled using *AccuRate* software based on heating and cooling needs. The heating and cooling energy requirements from *AccuRate* were used as input data in *SimaPro*. AccuRate produces data in the format of MJ/m^2.per annum; this number was put directly into the *SimaPro* model.

The economic investment was calculated using an LCC approach. The data input to the LCC analysis for the construction, maintenance and disposal phases were sourced from a standard construction cost guide (Rawlinsons 2010) and published literature (IST 2011). Operational energy costs were sourced from a price comparison report from Hyland (2011).

Two modelling approaches were used for the system analysis. Single-Objective Optimisation (SOO) was used to identify single optimal solutions for assemblage designs. In SOO, one variable is optimised at a time. Multi-Objective Optimisation (MOO) was used to identify a set of optimal solutions. In MOO, more than two or multiple variables were optimised at a time.

3.3 CASE SELECTION AND MODELLING STEP

This research addresses the optimised use of material in floors, walls, and roof designs in a residential house. It investigates how various combinations of these assemblage designs with various materials type, design and insulation options can minimise cost and environmental impact. Alternative configurations were evaluated and compared. A case study approach was undertaken. It allows for an in-depth examination within a real-life context for the purposes of investigation, development and testing, This is the most common approach in LCA of buildings, for example Blanchard & Reppe (1998), Carre (2011), Frenette et al (2010), Iyer-Raniga & Wong (2012), . The case study house was modified with these alternative configurations. The effect of the alternative walls, floors and roofs on the houses economic and environmental impact was analysed.

The following six steps were undertaken in modelling: firstly, common materials and design techniques for individual building element were identified. Secondly, assemblage designs with different materials were analysed based on building thermal performance (star ratings) using *AccuRate*. The predicted heating and cooling energy was used as input data into *SimaPro*. Thirdly, a streamlined LCA approach was undertaken using PRé's *SimaPro* (version 7.3) software to predict whole life cycle environmental impacts. Fourthly, LCC were calculated using building costs from Rawlinson's Construction Cost Guide as well as Hyland (2011). Then, various optimisations approaches were undertaken to identify both single optimal and a set of multiple solutions. SOO was applied to identify a single optimal solution for each objective. Finally, MOO was applied to identify a set of optimal solutions. MOO was used to identify suitable trade-off relationships between objectives.

Assemblage design options for building elements (that is walls, floors and roofs) were chosen from a library of designs in *AccuRate*. Each assemblage was designed in accordance with Building Code of Australia Guideline (BCA 2005). The effect of assemblages design on LCA and LCC were evaluated using two experimental designs. Firstly, one variable was varied at a time. For example, when different wall assemblages were designed, the floor and roof were kept constant (based on the case study house). For roof assemblage designs, floor and wall were kept constant. Similarly, for floor assemblage designs, wall and roofs were kept constant. The assemblage designs were further constrained to achieve a specific thermal performance in terms of star rating. Secondly, the optimum wall, floor and roof assemblage designs were aggregated as one whole house design. The LCA and LCC were evaluated for each design with various different assemblages as well as the whole building and whole life cycle context.

3.4 APPROACH OF MODELLING STEP

3.4.1 Approach to calculation of the Bill of Quantity

The quantity of the materials required for the building is calculated mathematically as the Bill of Quantity (BOQ). The approach to calculating the BOQ is a standard practice across the construction industry. The material quantities are calculated from house plans, drawing dimensions, suitable material properties and assemblage designs.

The BOQ calculated in this study was used standard factors published in industry references. Relevant material properties (that is density and mass) were found in the literature (Rawlinsons 2009; Staines 2004). On-site construction losses from cutting and fitting were included in the estimates (at 5%). This approach was selected because it is a useful simplification that has been used in several relevant LCA studies of residential housing in Australian and elsewhere (Blanchard & Reppe 1998; Rouwette 2010; Szalay 2007). These studies also used 5%.

3.4.2 Approach to calculation of operational energy

Operational energy calculations for heating and cooling were undertaken through estimation of heat loss and gain relative to a particular climate. The assessment was undertaken based on the relationship between the thermal conductivity of the building components for the particular indoor and outdoor climatic conditions.

AccuRate (V1.1.4.1) software from the Commonwealth Scientific and Industrial Research Organisation (CSIRO) was used to estimate operational energy (i.e. heating and cooling) requirements. This popular tool is recommended by the Australian Nationwide House Energy Rating Scheme (NatHERS) as well as the Building Code of Australia, and has been validated through BESTEST (Delsante 2004; Morrissey & Horne 2011). *AccuRate* includes an extensive database of materials that allows the user to modify building elements. It contains a wide selection of wall, floor and roof assemblage options. The user can specify the materials and construction techniques, insulation levels, windows size and orientation, shading, ventilation, overshadowing, colour of indoor surfaces, geographical location and external wall orientation (Dewsbury et al 2009; Seo et al 2005). The various assemblages and designs were chosen from those available in *AccuRate*.

Table 3.1: Area adjusted energy and star band score thresholds for the Brisbane climate

NatHERS climate zone	***Star band score and area adjusted energy (MJ/m²*.annum)***									
	1 star	2 star	3 star	4 star	5 star	6 star	7 star	8 star	9 star	10 star
Brisbane (Zone 10)	203	139	97	71	55	43	34	25	17	10

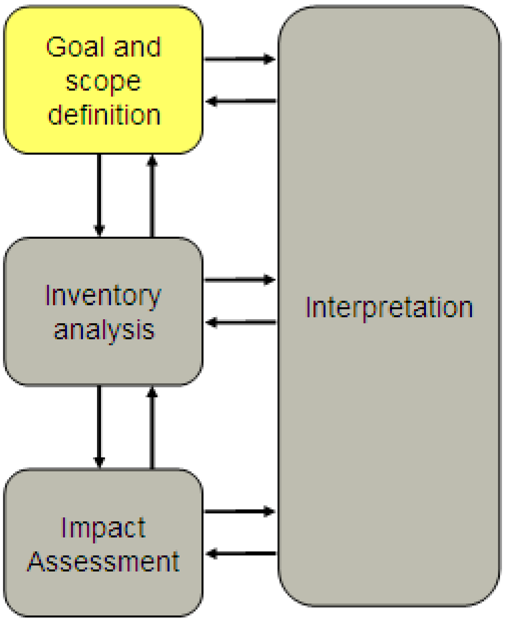
AccuRate predicts area adjusted energy requirements for space heating and cooling in units of MJ/m^2.annum basis. Based on area adjusted energy requirements and the NatHERS star band score thresholds, the house design is rated by *AccuRate*. Table 3.1 gives an example of the area adjusted energy requirements and star band scores thresholds for the Brisbane climate. The thresholds are based on the Protocol for House Energy Rating Software published by the Australian Building Codes Board (ABCB 2006). The higher the star rating, the lower the cooling or heating is required by occupants to stay comfortable.

Heating and cooling energy loads (MJ/m^2.annum) were then adjusted for floor area as well as for efficiency of energy source and appliance. The details of how the assessment was performed and assumptions are discussed in detail in Section 4.5.1.

3.4.3 Approach to undertake LCA

A streamlined LCA approach was undertaken using PRé's *SimaPro* (version 7.3) LCA software. The ISO 14044 guidelines on LCA methodology were used. Figure 3.2 shows the methodological approach followed in this LCA study. It consists of four distinct analytical steps: (1) Goal and scope definition; (2) Life Cycle Inventory (LCI) analysis; (3) Life Cycle Impact Assessing (LCIA) and (4) Interpretation of results.

Figure 3.2**:** Stages of an LCA



3.4.3.1 Goal and scope definition

Statements are made in this phase defining the functional unit, expected product and assumptions. This phase identifies the audiences, system boundaries and purposes of the LCA. The functional unit of this LCA is the life cycle of one 101m^2 residential dwelling over a fifty-year lifetime. The life cycle includes construction, operation, maintenance and disposal. Results are presented based on whole building as well as building life cycle stages. The rationale for selecting the functional unit, assumptions and system boundaries are discussed in Section 4.6.2.1.

3.4.3.2 LCI data collection and analysis

The Life Cycle Inventory (LCI) analysis involves collecting, compiling and modelling the product systems. It contains all the relevant inputs (i.e. energy, mass flow and water) and outputs (emission and solid waste) of the systems for the life cycle, cradle to grave or cradle to gate. The outcome of this phase is a quantitative inventory including resource consumption and waste emissions from production to demolition.

A total amount of each material is calculated then corrected to mass or other suitable unit used to create a model in the LCA software. Process associated with production and transports are included, for example, transportation within and between life stages.

3.4.3.3 Life Cycle Impact Assessment (LCIA)

This study used the Australian Impact Method with Normalisation including Cumulative Energy Demand (CED). In this LCIA method, impact categories include greenhouse gas (CO_2 equivalent) emission, cumulative energy demand (embodied energy), water use, solid waste, acidification potential, eutrophication, land use and photochemical oxidation potential. This study selected four impact categories: greenhouse gas (GHG) emission, Cumulative Energy Demand (CED), water use and waste impact. The rationale of selecting these four is discussed in Section 4.6.2.4.

3.4.3.4 Interpretation of results

In this phase, the LCI analysis and LCIA results are discussed in an objective and informative manner to reach conclusions and formulate recommendations. To confirm the validity and extend the applicability of the results, the results are compared quantitatively and qualitatively to similar published studies. Sensitivity and uncertainty analysis are also conducted to qualify the results.

3.4.4 Approach to undertake LCC

LCC estimates all relevant costs throughout the life period. It includes construction costs, maintenance, repair, and replacement costs, energy costs, and residual values. It estimates all costs at their Present Value (PV).

A general LCC formula is given in equation (1) (ASTM 2002; DLMC 2007; Schade 2007; Snodgrass 2008; Sterner 2002):

LCC = I + Repl - Res + E + W + OM&R + O..(1)

Where LCC: is total life-cycle cost in present value (PV) dollars

I: is the initial cost

Repl: is the PV of capital replacement costs

Res: is the PV of residual value (resale value, salvage value) less disposal costs

E: is the total energy cost (PV)

W: is the total water costs (PV)

OM&R: is the total operating, maintenance and repair cost (PV)

O: is the total other costs (administration costs, financing costs) (PV)

All initial and future costs are combined in an LCC analysis. The present values of future costs are calculated using today's prices, and an estimate of future inflation equation (2), and a suitable discount rate equation (3) (DLMC 2007; Langstone 2005). Because of future risk, the discount rate exceeds the inflation rate. The inflation rate used in this study is 3%, which is the average of the Australian inflation rate over the last 10 years (Rate Inflation 2011). The discount rate used is 6%, which is recommended for the construction industry by the Australian Department of Infrastructure (2005).

$$FC = PC(1+f)^n \quad \text{(2)}$$

Where FC=future cost; PC= present cost, f=inflation rate and n= number of years

$$PV = FC/(1+d)^n \quad \text{(3)}$$

Where, PV= Present Value; FC=future cost, d= discount rate and n= number of years

The construction costs include material and labour costs. The operational energy costs include the energy's unit prices and service charges over a 50-year lifetime. The maintenance costs include material replacement, labour and repainting costs over a 50-year lifetime. Disposal costs were included for both major renovations and final demolitions. Construction, labour and disposal costs were estimated using the standard set of relevant constants given in Rawlinsons Cost Guide (2010). Sample labour constants are given in (Appendix 4 E1). The reader is referred to the guide for the costs that were actually used. Note that the guide also specifies standard methods for calculation. The operational energy costs were based on local utility rates from Hyland (2011). Delivery costs were not included because there is no data available. The frequency of maintenance was based on maintenance schedule discussed in Section 4.6.2.2.

3.4.5 Approach to model optimisation

There are many different optimisation approaches. In this study, linear programming (LP) was used for optimisation. In this approach, variables are minimised or maximised as a linear function of the outputs of the activities. The rational and alternative approaches to this optimisation are discussed in Section 3.5.4.

This section describes the optimisation algorithm and software used in this study. The computer software package *LINDO* (Linear Interactive and Discrete Optimizer) was used. *LINDO* may be employed to solve linear, integer and quadratic programming problems.

An LP model of a system has the form (Azapagic & Clift 1999):

$$Minimise \;\; Z = \sum_{i=1}^{I} z_i x_i \quad \text{..} \; (4)$$

Where Z = Objective function

z_i = Coefficients in objective function

x_i = Output of activity

Which subject to

$$\sum_{i=1}^{I} a_{j,i} x_i \leq e_j \qquad j = 1,2,........, J \quad \text{..} \; (5)$$

Where, $a_{j,i}$ = Input/Output coefficient for a process

e_j = effective target

And $x_i \geq 0 \qquad i = 1,2,........, I$

Equation (4) represents an objective function. For this study, objective functions may be either economic or environmental impacts. In selecting the optimal combination of a building's life cycle costs, the optimisation model may be re-written in equation (6), if one variable is to be minimised:

$$\text{Minimise } Z = (z_1x_1+z_2x_2+\ldots\ldots+z_ix_i)\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

Where, x_1, x_2 and x_i are the building components. z_1, z_2 and z_i are the cost coefficients that determine the costs for each case. Total minimised costs will be the summation of costs over the life cycle of a house.

Equation (5) is the constraint in the system where a_{ji} represents environmental impact, i of component j. It represents quantitative measures of material and energy flows including inputs, flows within the economic system, and outputs. The constraint (e_j) reflects maxima such as the house owner's maximum budget.

If only one variable is minimised at a time, the SOO approach can be used. In such a case, the other variables are constrained to the average or other suitable target. If multiple variables are to be minimised a MOO should be used. There are various approaches to MOO. These include combining individual objective functions into a single composite function or moving all but one objective to the constraint set (Hawe & Sykulski 2008; Konak, Coit & Smith 2006). In this study, weighted sum approach was used, where MOO is transformed to SOO. In this approach, a weight is assigned to each normalised objective function so that the problem is converted to a single objective problem with a scalar objective function (Konak, Coit & Smith 2006). If multiple variables are to be minimised such as cost and multiple environmental impact indicators then equation (6) can be re-written as:

$$\text{Minimise } Z = w_1(z^*_1x_1) + w_2(z^*_2x_2) + \ldots\ldots\ldots\ldots + w_i(z^*_ix_i)\ldots\ldots\ldots\ldots(7)$$

Where, $z^*_ix_i$ is the normalised objective function of z_ix_i and $\{w_1+w_2+\ldots.+w_i = 1\}$.

In this approach, the user or stakeholders may provide the weights. Solving a problem with the objective function in equation (6) for a given weight vector $w_i = \{w_1, w_2 \ldots.w_i\}$ yields a single solution.

In MOO, two or more objectives can be optimised, and one or more solutions are generated (Shuqing 2005; Wang 2005). In the real world, optimising all the objective functions may be too complex to be feasible (Kolokotsa et al 2009; Konak, Coit & Smith 2006; Shuqing 2005). One common approach to reduce complexity is a trade-off solution. MOO is used to produce a trade-off table (Alegría & Calderón 2006; Azapagic & Clift 1999; Zacharia 2003). The trade-off table is used to analyse the relationships between the objective functions. The decision maker can then apply quantitative criteria on weighted values to the set of solutions for multiple objectives.

3.5 A CRITIQUE OF MODELLING TOOLS

3.5.1 Energy rating software

There are several software programs that can be used to rate the energy efficiency of homes. These include *AccuRate, Firstrate5, Green Star* and *BERSpro*. A competitor of *AccuRate, Firstrate5* was developed by Sustainability Victoria, and is predominantly used in Victoria, Australia. *Firstrate5* produces results similar to *AccuRate*, as they use the same underlying calculation engine and have a similar database of materials (Delsante 2007). *Green Star* is another simulation program for rating commercial buildings, developed by the Green Building Council of Australia (Arnold 2011).

AccuRate was chosen for this study because *AccuRate* is an approved program to rate homes in tropical and sub-tropical environments. It meets the energy efficiency provisions of the Building Code of Australia. *AccuRate* is a newer version of the Australian Nationwide House Energy Rating Scheme software NatHERS. It is the main software used in Australia. *AccuRate* includes an extensive database of materials that allows the user to modify construction elements. *AccuRate* has the options to select varieties of material, insulation and air gap to design the assemblages. *AccuRate* also has the options to select varieties of windows size and orientation, shading, ventilation, overshadowing, colour of indoor surfaces and geographical location (Dewsbury et al 2009). The user must specify the materials and construction techniques.

3.5.2 LCA software

A variety of LCA modelling software are available in different regions, such as *GaBi* and *SimaPro* in Europe, and *ATHENA* and the *BEES* in the US and Canada (Szalay 2007). A major limitation of these LCA software is that they require current, region specific and valid LCI data to obtain an accurate analysis.

ATHENA is a highly rated program used in many studies in the US and Canada. Its LCI are based on data from US and Canadian companies and building practices

(Szalay 2007; Yellishetty et al 2009). Hence, *ATHENA* is not recommended for use in an Australian scenario.

The Building for Environmental and Economic Sustainability (*BEES*) program is another North American environmental impact software program that complies with ISO 14044. It measures the environmental performance of building products using a life cycle approach (Nebel 2006; Szalay 2007; Zacharia 2003). *BEES* represent information at a high level of aggregation. The underlying LCA data is inaccessible to users (Zacharia 2003). All outputs are given in terms of two scores for environmental and economic impacts, so there is no choice over individual impact indicators. Additionally, *BEES* offers only generic options for some building products and no options for experiments with size and spacing of steel framing joists or with the sheathing thickness (Zacharia 2003). Hence, *BEES* is not suitable for a study looking at modifying building elements, as in this study.

GaBi LCA software is another software compliant with ISO 14044 standards (Szalay 2007). This tool calculates the relevant environmental category indicators using various impact assessment methods. Its LCI data are mostly average German industry data (Szalay 2007). *GaBi* might be used for Australian scenario, if AusLCI database can be accessed.

SimaPro LCA tool was chosen for this study as the LCA community have identified it as the LCA tool of choice (Henricksen 2006), as well as for ease of comparison with other relevant studies. Many of the whole life cycle assessment studies on Australian buildings used *SimaPro* (Carre 2011; Iyer-Raniga & Wong 2012; Rouwette 2010).

The Australian Life Cycle Inventory (AusLCI) was chosen for this study because it is specific to the Australian region and the case study house was built in Australia. It has been used in a number of other Australian studies (Chen et al 2011; Newton et al 2001; Tharumaharajah & Grant 2006).

The world leading eco-invent (Swiss based) database was also used for any materials not available in AusLCI. This approach has been used in a number of other Australian studies (Chen et al 2011; Tharumaharajah & Grant 2006).

In AusLCI unit processes were selected that have Australian data or have been adjusted for the Australian Building Industry and the database based on the eco-invent database. Eco-invent database was used for any other unit processes that were not available in AusLCI.

3.5.3 LCC method

Two approaches commonly used in the literature (i.e. RS Means and Dodge Unit Cost Guide) offer similar information but these are suitable for the North American regions (OCS 2001; Zacharia 2003). RS Means is an online cost data and estimating tool. It estimates costs based on US and Canadian prices in US customary units (OCS 2001).

The Dodge Unit Cost Guide uses US national average costs and its material costs are estimated from building product manufacturers, dealers, supply houses, distributors, and contractors. Wage rates are collected locally in both approaches (OCS 2001). Both are not recommended for use in an Australian context.

Rawlinsons Construction Cost Guide provides costs based on Australian average cost data. Quantity surveyors and construction cost consultants have used Rawlinsons Construction Cost Guide for residential projects throughout Australia since 1953 (Rawlinsons 2010). All the relevant economic factors of material, labour and demolition costs can be estimated using Rawlinsons. The operational energy costs can be estimated using local utility rates published by Hayland (2011). Therefore, Rawlinsons Construction Cost Guide is superior to RSMeans and Dodge Unit Cost Guide for this particular project as it is for the Australian region.

3.5.4 Optimisation software

A variety of software is used in optimisation studies of residential buildings, as discussed in Section 2.6.2. Programs such as EXCEL, MATLAB, LINDO and LINGO are used.

EXCEL may be used to show a comparison between two or more data sets. It shows data points plotted between the x and y-axis of two or more sets of data. EXCEL is particularly useful when a problem has small data sets. However, it does not consider any constraints. A constraint is defined as a limit to a solution to a particular optimisation problem that the solution must satisfy. For example “the cost must be less than $X”, where an optimum cost is needed.

MATLAB has an optimisation toolbox for mathematical programming. It includes functions for linear, quadratic, binary integer programming, nonlinear optimisation and multi-objective optimisation (The MathWorks 2011). It is widely used for standard and large-scale optimisation but is rarely used for small-scale optimisation problems.

LINDO Systems is a leader in mathematical optimisation. It provides fast, easy to use tools (LINDO Systems 2012). LINDO minimises or maximises the objective functions subject to a set of constraints using linear or quadratic or and integer programming (Khan & Min-Allah 2011; Zacharia 2003). The constraints may be linear equalities or inequalities. LINDO can treat the problem as an integer-programming problem, if all variables can be realistically represented as non-negative integers.

LINGO is another optimiser from LINDO Systems with a set of solvers for linear, integer, and nonlinear models. LINGO is a more advanced and comprehensive tool than LINDO, which is useful with larger models (LINDO Systems 2012; Zacharia 2003).

LINDO is best for use when the variables can be represented as non-negative integers, as in this study. LINDO can deal effectively with complex problems yet is simple to use (Khan & Ardil 2009; Khan & Min-Allah 2011; Zacharia 2003). It can be used up to 100 constraints and 200 variables (LINDO Systems 2012; Zacharia 2003). Hence, LINDO is useful and easy to handle, and hence was selected for this study, as the problem size is relatively small.

3.6 SUMMARY

This chapter describes the methodological framework and the methods used in this study. It discusses the approaches to model operational energy requirements. It also discusses the approaches to LCA and LCC calculations and optimisation for residential buildings. The preference software tools are *AccuRate*, *SimaPro* and *LINDO* for evaluating operational energy, environmental impact and optimisation, respectively. All the relevant economic factors of material, labour and demolition costs can be estimated using Rawlinsons Construction Cost Guide.

The tools and techniques presented here are demonstrated through a case study residential house discussed in Chapter 4. LCA and LCC results for the case study house and other modified houses are presented in Chapter 4, 5, 6 and 7 along with discussions. Optimisation results using *LINDO* are presented in Chapter 8 along with discussion.

CHAPTER 4: CASE STUDY SELECTION AND MODEL VALIDATION

Introduction; Case study house description; Changes to the case study house; Data description; Modelling assumptions and justifications; Results of the case study house; Sensitivity analysis; Summary

4.1 INTRODUCTION

Using the methodology described in Chapter 3, this chapter describes all aspects of the case study house, and the changes made to the case study house for improvement options. It includes descriptions of the assemblage designs, bill of quantity (BOQ) and LCA and LCC model inputs. It describes the data requirements and modelling inputs along with rationale and justification. The assumptions and simplifications regarding data collection, assessment and model validation are also described in detail to enable the reader to understand and assess the validity of the results presented in Chapters 5, 6 and 7.

4.2 CASE STUDY HOUSE DESCRIPTION

A typical Australian residential townhouse was selected as the case study house for this project because a house plan and Bill of Quantity were available to the project team. Such documents are not available in the open literature, and LCA and LCC cannot be completed without them. Townhouse/unit is the second most popular type after detached house in Australia (ABS 2012), with 21% of dwellings. Another reason is that higher density housing (attached townhouse/units) is the most common in Australian capital cities. For example, nearly 45% of all new dwellings were either attached or semi-detached dwellings in Melbourne for the decade from 1991 to 2001 (DSE 2003).

The case study house was built in Brisbane, Australia in 2006. A member of the Building Designers Association Queensland (Jerrin Designs: Job No. 585.02) designed it. It complied with the 2005 Building Code of Australia (BCA) deemed-to-satisfy (DTS) provisions (BCA 2005), which did not require new buildings to have any particular building thermal performance or star energy rating. Since that time the DTS provisions have been updated and now new buildings are required to have a star energy rating of at least 6.0 (Building Commission 2011). Hence, the star rating for this building of 3.6 star rating fully met BCA requirements, but is lower than would be built today. The low star rating of this building then limited the achievable star rating when only the building envelope material was varied.

The architectural layout of the case study house, a town house, is shown in Figure 4.1 and Figure 4.2. Unit 2 (shown by the dotted area) was selected, as the case study house. The more detailed sets of drawings for unit 2 are given in Appendix 4.A and Appendix 4.B.

Figure 4.1 : Case study house drawings for ground floor (attached unit no. 2)

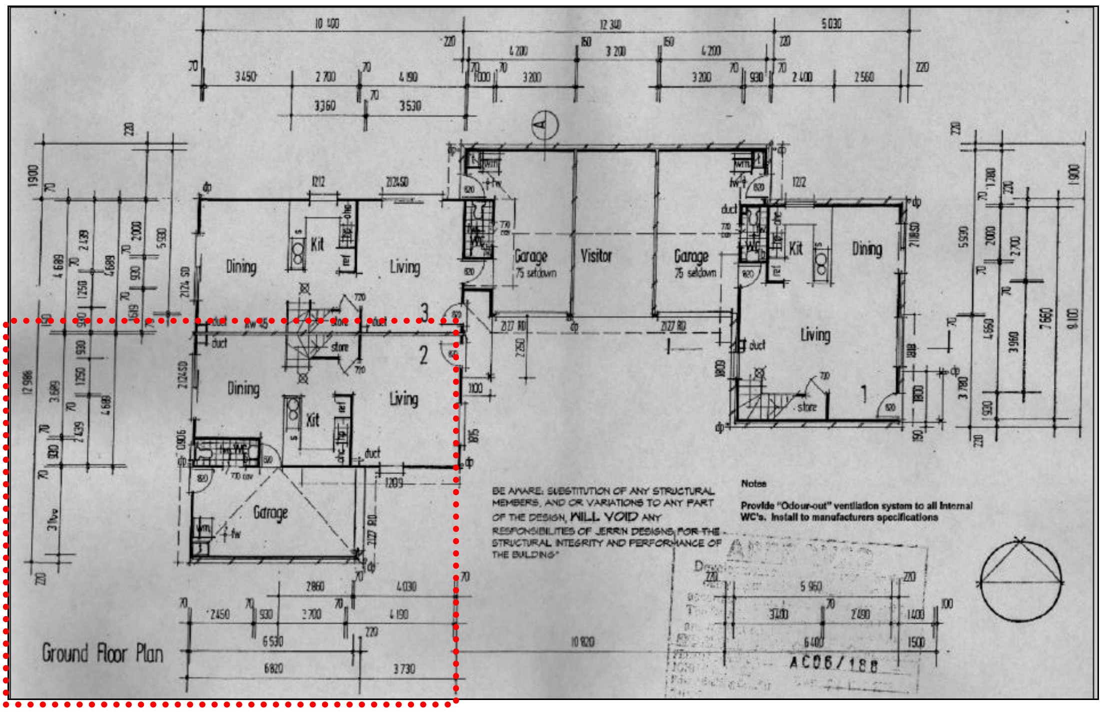
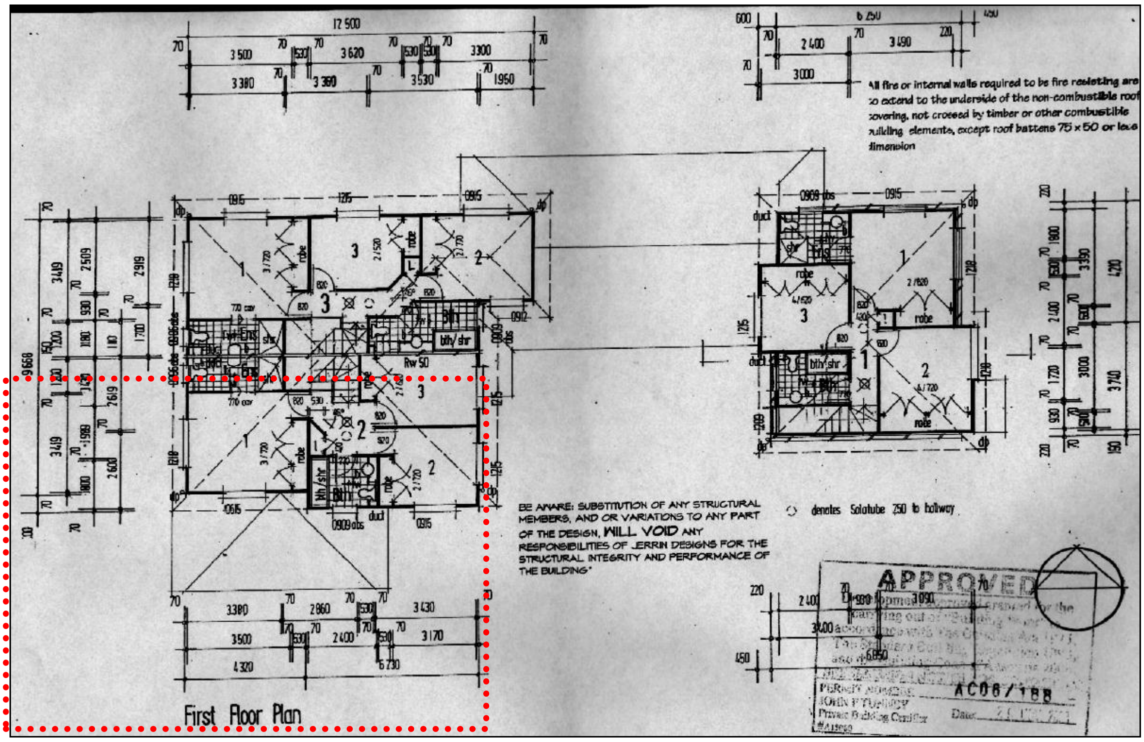


Figure 4.2 : Case study house drawings for upper floor (unit 2)



The residence (unit 2) is a double storey, attached timber frame dwelling with face brick and a concrete slab on the ground floor. The house has three bedrooms and an attached garage. The upper floor (Figure 4.2) comprises a master bedroom with an en-suite and two smaller bedrooms and second bathroom. The general description of the case study house is as follows.

4.2.1 Foundations

The foundations consist of reinforced concrete strip footings, edge and internal beams. The edge beam and internal beam extend 200mm into the founding material. The foundation sits in soil that is naturally stiff silty clay. The house ground floor is 10.4m in length and 4.8m in width. The garage floor is 6.8m in length and 3.3m in width. The ground floor of the house and garage floor are made of 100mm concrete slabs. The reinforced concrete has a specification of 20MPa at batching plant.

4.2.2 Floors

The total house floor area (ground and upper) is 101m². The garage floor is 21m². House and garage have concrete slabs on the ground floor, as discussed above. The floor tops are carpet in upper floor, except in the kitchen, wet areas and garage. Timber is installed over the concrete slab on the ground floor.

The flooring systems at the first floor have 170mm x 45mm hardwood floor joists and 150mm x 75mm floor bearers. The joists and bearers are spaced 450mm and 1800mm apart, respectively. The floor decking is 12mm ply wood. There is no insulation used in the ground floor assemblages. Glass fibre batt (R1.5) insulations are used in the first floor assemblages. Tiles are used in wet areas and kitchen. Bare concrete is used in the garage only.

4.2.3 Exterior and interior walls

The wall area consists of external and internal walls, and an attached wall. The house exterior walls are clad with fibre cement (FC) sheet, and the garage with decorative brick veneer. The attached walls between unit 1 and 2 are brick (generic extruded clay brick). The bricks are sealed with uncoloured cement plaster (15mm). All internal walls are built with 10mm plasterboard on stud.

The wall frames are 70mm x 38mm kiln dried pine timber stud spaced 450mm apart. Glass fibre batt (R1) insulation is placed in the stud cavity to improve the building thermal performance (Figure 4.3). The exterior walls also have a 3mm thick vapour barrier (building paper) and a small 40mm air gap.

4.2.4 Roof and ceiling

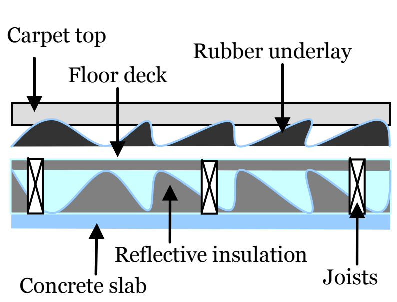
The roof is a gable roof with a 25^{o} pitch. The total rooftop area is 125m^2. The rooftop is colour coated concrete tiles. The rooftop has a 3mm thick vapour barrier (polyethylene) and a layer of glass fibre batt (R2) insulation with a small 40mm air gap.

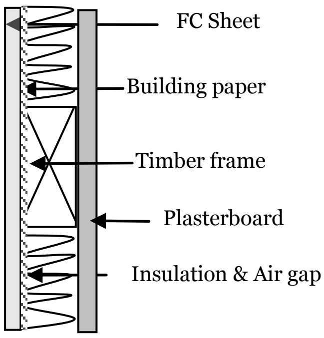
150mm x 50mm softwood timber joists, spaced 450mm apart, support the upper and ground floor ceiling. The ground floor ceiling has glass fibre batt (R1.5) insulation in the ceiling cavity. The upper floor ceilings are 10mm smooth finish plasterboard with glass fibre (R2.5) batt insulation in the ceiling cavity.

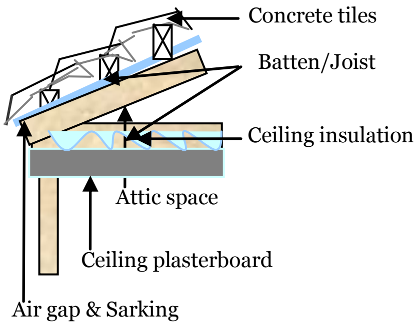
Not to scale sketches of the essential elements of the case study house are shown in Figure 4.3. They show the arrangement used in floor, wall and roof assemblages.

Figure 4.3: Floor, wall and roof assemblage's arrangements of case study house

Floor	Wall	Roof and Ceiling
Carpet/timber/tiles top Carpet underlay Plywood floor deck (12mm) Reflective insulation Timber floor bearers (150mm × 75mm) Concrete slab on ground (100mm)	FC Sheet Building paper (reflective foil) Insulation and Air gap Softwood plates, studs, noggins Plasterboard	Concrete roof tile Air gap (40mm) Sarking (Reflective insulation) Softwood rafters, battens Softwood ceiling joists Ceiling insulation Plasterboard







4.2.5 Door and window

The doors and windows are shown on the house plan (see in Figure 4.1 and Figure 4.2). The total doors and windows area is 22m^2. The external doors have pine frame with lock set with a dead bolt. The internal doors are built of timber flush panel. The garage door is a remote controlled roller door with a 2.1m x 2.7m colour bond panel. The windows are double-glazing with aluminium framing and powder coating. Fly screens are not included. There is one external sliding door in the dining area. The sliding door is double-glazing with similar construction to the windows.

4.2.6 Painting and repainting

The external walls (FC sheet and decorative brick) are painted with two coats of exterior of acrylic. The internal and attached wall areas have two coats of interior matt acrylic, except for the tiled areas. The door and window framings are painted with two coats exterior of acrylic. The internal ceiling areas have two coats of matt acrylic. The rooftop is painted with two coats of exterior acrylic glazing. The timber floor top is painted with two coats of acrylic varnish.

4.3 CHANGES TO THE CASE STUDY HOUSE

The assemblage arrangements of case study house shown in Figure 4.3 were modified to alternative floor, wall and roof assemblages. As discussed in Section 3.3, the effects on the environmental impact of the house design of the modified assemblages were evaluated using a constrained experimental design. One variable from floor, wall and roof was varied at a time. When the wall assemblage design was modified, floor and roof assemblages were as in the case study house. These results are given in Chapter 5. Similarly, for the roof and floor assemblage designs, the other assemblages were as in the case study house. These results are given in Chapter 6 and 7. In Chapter 8, all the assemblage designs are used for Mathematical Programming optimisation.

The modified floor, wall and roof assemblage designs were selected based on material type, assemblage type and thermal performance. Each design provided a particular star rating when assessed in *Accurate*. The designs were based on commonly used components, complied with BCA guidelines such as maximum wall thickness for wall designs. The operational energy for each designs and the BOQ for its components were used as input data to the LCA and LCC models. The designs were evaluated for operational energy requirements in one climate only (Brisbane). The changes made to the case study house's floor, wall, and roof assemblage designs used in this study are discussed below.

4.3.1 Modified floor assemblage designs

The modified floor assemblages are shown in Table 4.1, showing the assembled layers from top to bottom. The modified floor assemblage designs used flooring types, and various floor top materials, type and position of insulation and air gap for first floor. The choices of flooring options adopted were guided by those available in *AccuRate*, which includes models of those in common use in Australia. A concrete slab on ground type floor was chosen, as the case study house has a concrete slab on ground. Concrete slab on ground is a popular floor type in Australian residential floor designs (Kapambwe et al 2008; Staines 2004; QUT 2011).

Table 4.1: Selected floor assemblages arrangements adopted from *AccuRate*

Name of the floor design	Ground floor (Dining and Living)	Ground floor (Wet areas & kitchen)	Upper floor (bed room, veranda and corridor)	Upper floor (wet areas)
Timber floor	T&G hardwood (19mm) Ply wood (12mm) Concrete slab: 2400kg/m3	Ceramic tiles Ply wood (12mm) Concrete slab: 2400kg/m3	T&G timber board pine (19mm) Ply wood (12mm) Glass fibre batt: R1.5 Floor bearers, joist Plaster board	Ceramic tiles (8mm) Ply wood (12mm) Floor bearers, joist Plaster board
Carpeted floor	Carpet (10mm) Carpet underlay (10mm) Ply wood (12mm) Concrete slab: 2400kg/m3	Ceramic tiles Ply wood (12mm) Concrete slab: 2400kg/m3	Carpet (10mm) Carpet underlay (10mm) Ply wood (12mm) Glass fibre batt: R1.5 Floor bearers, joist Plaster board	Ceramic tiles (8mm) Ply wood (12mm) Glass fibre batt: R1.5 Floor bearers, joist Plaster board
Ceramic tiled floor	Ceramic tiles Ply wood (12mm) Concrete slab: 2400kg/m3	Ceramic tiles Ply wood (12mm) Concrete slab: 2400kg/m3	Ceramic tiles (8mm) Ply wood (12mm) Rock wool batt: R1.5 Floor bearers, joist Plaster board	Ceramic tiles (8mm) Ply wood (12mm) Floor bearers, joist Plaster board
Mixed Designed floor	Ceramic tiles Ply wood (12mm) Concrete slab: 2400kg/m3	Ceramic tiles Ply wood (12mm) Concrete slab: 2400kg/m3	T&G timber board pine (19mm) Ply wood (12mm) Glass fibre batt: R1.5 Floor bearers, joist Plaster board	Ceramic tiles (8mm) Ply wood (12mm) Floor bearers, joist Plaster board

Four floor tops (that are carpet, timber, tile and mix floor tops) over concrete slab were selected for the modified floor designs. The reason to choose the installation of these four floor tops over a concrete slab is that this assemblage design is common in newly built houses (Delsante 2007; DEWHA 2008; FWPRDC 2001). These varieties of floor tops were chosen for modelling because they have varied life cycle environmental impacts and life cycle costs. The mixed floor tops were chosen so that these may help to identify optimum options among all designs. The detailed results of these modified floor designs are discussed in Chapter 7.

The installation of timber, carpet, tiles and mix floor tops were chosen for upper and ground floor. For mixed floor tops, combinations of timber and ceramic tiles were used. The choice was on similar ground to the ground floor. The garage was modelled with bare concrete. The insulation was varied in type, thickness and arrangements, except in ground floor (no insulation is added in ground floor design). Insulation may be added with multiple arrangements to achieve better effects, depending on the climatic conditions. Typical arrangements were chosen in the modified floor designs. The structural components (i.e. bearer, joist and floor deck) and floor tops for garage and wet areas were as in the case study house for each design.

4.3.2 Modified wall assemblage designs

A detail definition of the essential element of the selected wall assemblage designs options are given in Table 4.2.

Table 4.2: Selected wall assemblages (outer to inner) adapted from *AccuRate*

Brick 3.6 star Not specified	**Brick 3.7 star** Brick Building paper (vapour barrier) Air gap (40mm) Softwood plates, studs, noggins Glass fibre batt: R1.5 Plasterboard	**Brick 3.8 star** Brick Building paper (vapour barrier) Air gap (40mm) Glass fibre batt: R1.5 Softwood plates, studs, noggins Glass fibre batt: R1 Plasterboard	**Brick 3.9 star** Brick Building paper (vapour barrier) Air gap (40mm) Glass fibre batt: R1.5 Softwood plates, studs, noggins Glass fibre batt: R1.5 Particleboard 19mm Plasterboard
Concrete 3.6 star AAC concrete block (100mm) Building paper (vapour barrier) Air gap (40mm) Softwood plates, studs, noggins Glass fibre batt (10mm) Plasterboard	**Concrete 3.7 star** AAC concrete block (100mm) Building paper (vapour barrier) Air gap (40mm) Softwood plates, studs, noggins Glass fibre batt (20mm) Plasterboard	**Concrete 3.8 star** AAC concrete block (100mm) Building paper (vapour barrier) Air gap (40mm) Softwood plates, studs, noggins Glass fibre batt: R1.5 Plasterboard	**Concrete 3.9 star** AAC concrete block (100mm) Building paper (vapour barrier) Air gap (40mm) Glass fibre batt: R1.5 Softwood plates, studs, noggins Glass fibre batt: R1 Plasterboard
FC sheet 3.6 star FC Sheet Building paper (vapour barrier) Air gap (40mm) Softwood plates, studs, noggins Glass fibre batt: R1.5 Plasterboard	**FC sheet 3.7 star** FC Sheet Building paper (vapour barrier) Air gap (40mm) Glass fibre batt: R1.5 Softwood plates, studs, noggins Glass fibre batt: R1.5 Plasterboard	**FC sheet 3.8 star** FC Sheet Building paper (vapour barrier) Air gap (40mm) Glass fibre batt: R1.5 Softwood plates, studs, noggins Glass fibre batt: R1.5 Particleboard: 19mm Plasterboard	**FC sheet 3.9 star** FC Sheet Building paper (vapour barrier) Air gap (40mm) Glass fibre batt: R1.5 Softwood plates, studs, noggins Glass fibre batt: R1.5 Particleboard: 33mm Plasterboard
Pine saw log 3.6 star Not specified	**Pine saw log 3.7 star** Pine saw log (75mm) Building paper (vapour barrier) Air gap (40mm) Softwood plates, studs, noggins Plasterboard	**Pine saw log 3.8 star** Pine saw log (75mm) Building paper (vapour barrier) Air gap (40mm) Softwood plates, studs, noggins Glass fibre batt: R1 Plasterboard	**Pine saw log 3.9 star** Pine saw log (75mm) Building paper (vapour barrier) Air gap (40mm) Glass fibre batt: R1.5 Softwood plates, studs, noggins Glass fibre batt: R1 Plasterboard
Weatherboard 3.6 star Weatherboard (12mm) Building paper (vapour barrier) Air gap (40mm) Softwood plates, studs, noggins Glass fibre batt: R1.5 Plasterboard	**Weatherboard 3.7 star** Weatherboard (12mm) Building paper (vapour barrier) Air gap (40mm) Glass fibre batt: R1.5 Softwood plates, studs, noggins Glass fibre batt: R1.5 Plasterboard	**Weatherboard 3.8 star** Weatherboard (12mm) Building paper (vapour barrier) Air gap (40mm) Glass fibre batt: R1.5 Softwood plates, studs, noggins Glass fibre batt: R1.5 Particleboard: 19mm Plasterboard	**Weatherboard 3.9 star** Weatherboard (12mm) Building paper (vapour barrier) Air gap (40mm) Glass fibre batt: R1.5 Softwood plates, studs, noggins Glass fibre batt: R1.5 Particleboard: 33mm Plasterboard

The modified wall assemblage designs included variations in wall claddings, insulation use and its position and air gap. The selected wall claddings are brick, autoclave aerated concrete block, FC sheet, pine saw log and weatherboard. The reason to choose these wall claddings is that a large portion of economic and environmental impacts is attributed to envelope materials such as brick and concrete (Blanchard & Reppe 1998; Zacharia 2003).

The chosen external wall claddings were modelled in *AccuRate* with various internal components selected so that the star rating varied from 3.6 to 3.9 star designs. Each design was varied such that it achieves a chosen star rating, for example, by adding slightly thicker insulation/double layer of insulation. According to Sustainability Energy Authority Victoria (SEAV n.d.), a double insulation layer can be used to achieve a higher star rating, where one layer is between the timber studs and the second layer is over the face of the studs. First, the case study house was modelled in *AccuRate*, found to have a star rating of 3.6 stars. Therefore, a 3.6 star rating was the first rating level chosen to assess the various wall cladding options. The upper limit of 3.9 stars was chosen, as this was the maximum rating possible for several of the wall claddings from this particular house design. Interestingly, brick and pine saw log design provides a minimum rating of 3.7 stars without any insulation used. Therefore, a design with 3.6 star-designed brick and pine saw log wall assemblages are not specified in Table 4.2.

The choices shown in Table 4.2 were limited to those available in *AccuRate* regarding building thermal performance. This is because those used in common practice guided the use and position of insulation type and thickness. The exception is for FC sheet and weatherboard cladding, where an additional layer of particleboard insulation was applied to achieve 3.8 and 3.9 star rating. Builders sometimes use this additional layer where sound insulation is needed such as, in music rooms (J. Marshall [J. Marshall Builder] 2011, pers. comm., 8^{th} February). In this study, this method was used to improve star rating.

The other structural framing components (that is stud, plate, noggin, joist and lintel) were assumed the same in all designs. The detailed results for these selected wall designs are discussed in Chapter 5.

4.3.3 Modified roof assemblage designs

The modified roof assemblage designs included variations of roof and ceiling types, rooftop materials, and the use and position of insulation and air gap in ceiling and roof design. Again, Sustainability Energy Authority Victoria (SEAV n.d.) indicate that a double insulation layer can be used to achieve a higher star rating, one between the timber battens/rafters, and one over the face of the battens/rafters. Those used in practice guided the choices of roofing options adopted. The chosen roofing types were gable, skillion flat and skillion pitch roof. The rooftop materials included metal and concrete tile. Different types of insulation were used with varying thicknesses to achieve better thermal properties. The structural components (roof battens and joists) were kept the same as the case study house.

The modified roof assemblage designs are given in Table 4.3.

Table 4.3 : Selected roof/ceiling assemblages arrangements adopted from *AccuRate*

<table>
<tr><th colspan="2">Tile roof with flat ceiling (3.6 star)</th><th colspan="2">Tile roof with flat ceiling (3.9 star)</th></tr>
<tr><td>Roof</td><td>Ceiling</td><td>Roof</td><td>Ceiling</td></tr>
<tr><td>Concrete roof tile (20mm)
Air gap (40mm)
Sarking (reflective foil laminates)
Softwood rafters, battens
Wool/polyester batt: R1</td><td>Softwood ceiling joists
Glass fibre batt: R1
Plasterboard</td><td>Concrete roof tile (20mm)
Air gap (40mm)
Sarking (reflective foil laminates)
Softwood rafters, battens
Glass fibre batt: R2.5</td><td>Polystyrene extruded: R3
Softwood ceiling joists
Glass fibre batt: R1
Plasterboard</td></tr>
<tr><th colspan="2">Metal roof with flat ceiling (3.6 star)</th><th colspan="2">Metal roof with flat ceiling (3.9 star)</th></tr>
<tr><td>Roof</td><td>Ceiling</td><td>Roof</td><td>Ceiling</td></tr>
<tr><td>Steel metal roof (2mm)
Air gap (40mm)
Sarking (reflective foil laminates)
Softwood rafters, battens
Wool/polyester batt: R1</td><td>Softwood ceiling joists
Glass fibre batt: R1
Plasterboard</td><td>Steel metal roof (2mm)
Air gap (40mm)
Sarking (reflective foil laminates)
Softwood rafters, battens
Wool/polyester batt: R2.5</td><td>Polystyrene extruded: R3
Softwood ceiling joists
Glass fibre batt: R2
Plasterboard</td></tr>
<tr><th colspan="2">Skillion flat metal roof (3.6 star)</th><th colspan="2">Skillion flat metal roof (3.9 star)</th></tr>
<tr><td>Roof</td><td>Ceiling</td><td>Roof</td><td>Ceiling</td></tr>
<tr><td>Steel metal roof (2mm)
Air gap (40mm)
Sarking (reflective foil laminates)
Cellulose fibre (loose fill): R1.5</td><td>Glass fibre batt: R1.5
Softwood ceiling joists
Plasterboard</td><td>Steel metal roof (2mm)
Air gap (40mm)
Sarking (reflective foil laminates)
Cellulose fibre (loose fill): R3</td><td>Polystyrene extruded: R3.5
Softwood ceiling joists
Glass fibre batt: R1.5
Plasterboard</td></tr>
<tr><th colspan="2">Skillion pitched-metal roof 3.6 star</th><th colspan="2">Skillion pitched-metal roof 3.9 star</th></tr>
<tr><td>Roof</td><td>Ceiling</td><td>Roof</td><td>Ceiling</td></tr>
<tr><td>Steel metal roof (2mm)
Air gap (40mm)
Sarking (reflective foil laminates)
Softwood rafters, battens
Polystyrene extruded: R1.5</td><td>Rock wool batt: R1.5
Softwood ceiling joists
Glass fibre batt: R1.5
Plasterboard</td><td>Steel metal roof (2mm)
Air gap (40mm)
Sarking (reflective foil laminates)
Glass fibre batt: R1.5
Softwood rafters, battens
Polystyrene extruded: R3</td><td>Rock wool batt: R3
Softwood ceiling joists
Glass fibre batt: R1.5
Plasterboard</td></tr>
</table>

Only two star ratings of 3.6 and 3.9 were modelled. The case study house has a star rating of 3.6 so this was the first lower level chosen. The 3.9 star rating was the higher level chosen because this is the highest level of rating obtained using commonly used materials and construction techniques.

4.3.4 Justification for the choice of assemblage designs

In this study, a variety of assemblage designs was chosen based on common material and construction technique that are available in *AccuRate*. *AccuRate* has the options to select varieties of material, insulation and air gap to model the houses. Another reason is that *AccuRate* allows the user to select varieties of material and construction techniques from the design library to model the assemblages (Dewsbury et al 2009). Hence, the user must specify the techniques based on local standards.

Table 4.4 shows a sample of the external wall, floor/ceiling and internal wall library options in *AccuRate*. Table 4.5 shows a sample material, insulation and air gap options to model floor, wall and roof assemblages. For simplicity, techniques were chosen similar to those used in the case study house.

Table 4.4 : Sample designs library adopted from *AccuRate*

External wall library	Floor/ceiling library	Internal wall library
Brick: plasterboard/wet plaster	Bare Ground	Plasterboard on studs
Cavity Brick: wet plaster	Concrete slab 100mm: Bare/bare	Pine logs: plasterboard
Reverse brick veneer: plasterboard	Concrete slab 100mm: Bare/plasterboard	Brick: wet plaster
Reverse brick veener: wet plaster	Concrete slab 100mm: carpet/bare	Brick: bare
Mud brick 300mm	Concrete slab 100mm: ceramic tiles/bare	Brick: plasterboard
Brick veneer (Un-insulated)	Concrete slab 100mm: tiles/plasterboard	AAC 100 mm: plasterboard
Concrete 100mm: plasterboard	Concrete slab 100mm: carpet/bare	Concrete block 90mm: bare
AAC 100mm: plasterboard	Plasterboard: R3.5/R2.5 bulk insulation	Concrete block: Plasterboard
FC Sheet (un-insulated)	Timber: bare/air gap/plasterboard	Rammed earth 300mm
Pine saw logs (75/150mm)	Timber: carpet/air gap/plasterboard	
Weatherboard (un-insulated)	Timber: tiles/air gap/plasterboard	

Table 4.5 : Sample material, insulation and air gap options in *AccuRate*

Material options	Insulation options	Air gap options
Metal/ tiles roof	Cellulose fibre (loose fill)	Ventilated air gap
Plywood/particle board	Glass fibre batt	Unventilated air gap
Soft board	Polyester/wool blanket	vertical air gap
Reflective blinds	Polystyrene expanded	Horizontal air gap
Window film	Polystyrene extruded	Inclined 45 degrees
Ceramic/vinyl tiles	Rock wool batt	Inclined 22.5 degrees
Carpet and carpet under lay	Wool/polyester batt	
Polycarbonate	Polyethylene foam	

4.4 DATA DESCRIPTION

4.4.1 Bill of Quantity

The builder's Bill of Quantity (BOQ) or "quantity take-off" provides a complete list of all the components and amounts used to construct a building. In this study, the BOQ is used as input data for *AccuRate*, LCA and LCC. The original BOQ was re-calculated into units suitable for *AccuRate*, LCA and LCC.

A sample with original and re-calculated units and quantities for the BOQ of the case study house is shown in Table 4.6.

Table 4.6: Sample BOQ of case study house

Data description	Original dimension		Re-calculated dimension	
	Unit	Quantity	Unit	Quantity
Excavation for footings	m^2	19.8	m^3	7.94
Concrete amount	tonne	49.2	m^3	20.5
Quantity of reinforcement	kg	971	tonne	0.97
Brick	m^2	45	kg	6544
Cement Mortar	kg	1439	m^3	0.77
Base plaster	kg	1254	m^3	0.67
External wall (FC sheet)	m^2	79.7	kg	876.9
Floor Bearers (150x75mm)	m	145.6	m^3	1.64

The "recalculated dimension" for each material was calculated from building specifications (such as for excavation of footings, the thickness was specified as 400 mm) or scaling factors (such as for concrete, the density is 2400 kg/m^3) or unit conversions (such as for reinforcement, 1 tonne is 1000 kg). For example, 19.8 m^2 or excavation for footings is multiplied by its depth of 400 mm to calculate the total 7.94 m^3. The figure of 400mm is taken from the Foundation Design X-Sections (Appendix 4.B1).

The BOQ of the elemental materials for the case study house is given in Appendix 4.C. Scaling factors were sourced from standard industry references, Staines (2004), Rawlinsons (2009) and other various published sources (Bajpai et al 2009; Carre 2011; Hammond & Jones 2008; Lawson 1996; Wood products Victoria 2007). The scaling factors used in this study are given in Appendix 4.D.

Two independent third parties checked the BOQ model data: an architect (I. Ahmed [RMIT University] 2011, pers.comm. 2nd June) and a local building materials manufacturer (D. Ashton [Mitek] 2010, pers. comm., 8th September).

4.4.2 BOQ and LCA

The quantity of each material is summed for the whole building to calculate the total amount of materials in the building. These total amounts are used as input data into the LCA model. The original BOQ was re-calculated into a unit suitable as life cycle inventory (LCI) data input using scaling factors (such as density and weighted mass), as discussed in above

The scope of this study was limited to effect of envelope materials on building LCA. Therefore, this BOQ did not include the interior decoration, stairs, kitchen sink, electrical wiring, lighting and appliances.

4.4.3 BOQ and Cost

The BOQ was also used to estimate costs of all building components at construction and maintenance. The unit costs were derived from various sources and were used to calculate the total life cycle costs. Sample elemental quantity and cost calculations are given in Table 4.7. The rate was estimated in Australian dollars (AUD).

Table 4.7: Sample elemental cost of case study house

No.	Description	Unit	Quantity	Rate/unit	Total (AUD)
1	Strip footing concrete	m^3	7.94	226	1794
2	FC sheet (external wall)	m^2	79.72	30.8	2455
3	Floor tiles in wet areas	m^2	14.98	40	599
4	Floor bearers (150x75mm)	m	145.6	13.05	1900
5	Concrete roof tiles	m^2	125.8	32.3	4064

Material, labour and equipment costs with overhead were calculated, and adjusted by multipliers suitable for the local economy, according to Rawlinsons (2010). Future maintenance costs were included in the costs calculations based on present value. A detailed table of costs of elemental material for case study house is given in Appendix 4.E.

In the following discussion, data quality and model validations are discussed.

4.5 DATA QUALITY AND VALIDATION

4.5.1 Operational energy data and result validation

A variety of tools is available to calculate operational energy usages of residential buildings (Chen 2010; Seo et al 2005). As discussed in Section 3.5.1, *AccuRate* was used to estimate annual operational energy (i.e. heating and cooling) requirements in this study. The reason to choose *AccuRate* as it includes an extensive database (libraries) and Australian standard climate data under NatHERS climate Zone. The user can specify the geographical location (i.e. NatHERS climate Zone). In this study, the operational energy was estimated using standard climate data for the Brisbane climate (NatHERS climate Zone 10).

To validate the results, an Australian energy-rating expert (J. Morrissey [RMIT University] 2010, pers. comm., 8th March) verified the energy rating simulations. Data for heating and cooling energy requirements were scaled up based on the air-conditioned appliance's efficiency, building lifespan as well as conditioned floor areas for the LCA model.

4.5.2 LCI data quality and validation

It is very important to use region specific, consistent and high quality LCI data for LCA modelling. The reason is that the outcome of a study might be valid for that region only and are not comparable to studies done in other regions (Horvath 1997; Reap et al 2008; Szalay 2007). The data used in this study were characterised in terms of geography, technology, age, collection method and representativeness. Sample LCI data of some major products and services are given in Table 4.8.

Table 4.8 : Sample LCI data of some products and services adopted from *SimaPro*

Product	Geography	Technology	Collection Method	Comments
Electricity	Australia	Average	Unknown	This is the main inventory for Queensland electricity. It is average of all suppliers.
Transport	Australia	Average	Unknown	Average of all suppliers; Inventory can be adjusted to suit specific load.
Pine saw logs	Australia	Mixed	Collects from typical forest management practices	Data was collected from a specific process and company. It included a mass based allocation between co-products.
Concrete (20MPa)	Australia	Mixed	Collects from production record and report	Inventory is developed based on data for specific company.

Data from the Australian region specific database (AusLCI) were used wherever possible. The Building Product Innovation Council (BPIC) updated the building materials database in 2009 (AusLCI 2009). Where data have not yet been collected from Australian sources, data from the European e*coinvent* database were used, after being "adjusted" for Australian electricity and transportation. In some cases, it is assumed that the manufacturing process is the same in Australia as in Europe. This approach has been used in several previous studies (AusLCI 2009; Chen 2010; Henriksen 2006; Tharumaharajah & Grant 2006). Typical sample material data and their brief descriptions are given in Table 4.9.

Table 4.9 : Typical sample LCI data for 'materials'

Materials	Data description
Timber	• Pine saw log: framing (AusLCI) • Hard wood: bearer and floor joist (AusLCI) • Transport: articulated truck 50km (AusLCI)
Brick	• Data from e*co-invent* • Electricity: (AusLCI) • Transport: articulated truck 50km(AusLCI)
Ceramic tiles	• Data from e*co-invent* • Electricity: (AusLCI) • Transport: articulated truck 50km (AusLCI)
Weatherboard	• Softwood with Alkyd resin preservative treatment (AusLCI) • Treatment process & resin: (e*co-invent)* • Transport: articulated truck 50km (AusLCI)
FC sheet	• Data from e*co-invent* (FC facing tile) • Density 1490kg/m³ • Transport: articulated truck 50km (AusLCI)
Concrete	• Data from AusLCI • Concrete at batching plant: (AusLCI) • Transport: concrete truck 30km (AusLCI)
Reinforcement	• 50% from e*co-invent* • 50% from AusLCI • Transport: articulated truck 50km (AusLCI)

Materials	Data description
Plasterboard	• Data from e*co-invent* • Gypsum plasterboard (e*co-invent)* • Production drying process • Transport: articulated truck 50km(AusLCI)
Glass fibre batt	• Data from AusLCI • Density 12kg/m³ • Australian electricity adjusted (AusLCI) • Transport: articulated truck 50km (AusLCI)
Paint	• Alkyd paint data for wall (e*co-invent)* • Alkyd varnish for timber floor (e*co-invent)* • Australian electricity adjusted (AusLCI) • Transport: articulated truck 50km (AusLCI)
Concrete Roof tile	• Data from e*co-invent* • Density is 2.4t/m³ • Transport: articulated truck 50km (AusLCI)
Particle-board	• Data from *Ecoinvent* • Australian electricity adjusted (AusLCI) • Density 620kg/m³ • Transport: articulated truck 50km(AusLCI)

For steel reinforcement, both European and Australian manufacturing process data were used. The reason is a significant impact variation between the two manufacturing process. If any data are not available in AusLCI or eco-invent, the LCI data were collected from the open literature, and verified the impact closely related with carbon and energy inventory study by Hammond & Jones (2008). For example, the LCI data for carpet were collected from Potting & Blok (1995).

Typical sample processing data and their brief descriptions are given Table 4.10.

Table 4.10 : Typical sample 'processing LCI data' requirements and description

Component	Data Description
Construction process	• Manual construction • Construction waste 5%
Transport Mode and distance	• 30t truck, average 28t load • Backhaul ratio 1.2 (load fraction/one way trip distance) • 50km from wholesale to site
Final Disposal	• Landfill only • 30km/truck distance to landfill • Garbage transit (Rigid truck)
Packaging	• Materials packaging excluded
Maintenance	• Replace at end of estimated lifetime • BCA guide line applies • Two coats for repainting
BOQ parameters	• Quantities calculated from plans • Typical density and mass value uses for scaling

Component	Data Description
Framing and Foundation	• Normal circumstances considers • Similar for all cases • BCA guidelines followed
Electricity	• Ducted cooling: Electricity • Australian production data: AusLCI
Natural gas	• Ducted heating: Natural gas • Australian production data: AusLCI
Doors	• European manufacturing process: *eco-invent* • Australian electricity adjusted
Windows	• European manufacturing process • Uncoated & flat glass: *eco-invent* • 2.27kg/m aluminium frame • 200km/truck distance

The LCA results from this study were compared with other recent LCA studies to verify the approach taken. An LCA expert (A. Carre [RMIT University] 2011, pers. comm., 15th February) reviewed and critiqued the LCA model, used in this study.

4.5.3 LCC data and validation

As discussed, material, labour and disposal costs data were derived mainly from Rawlinsons Construction Cost Guide (Rawlinsons 2010). Other elemental costs data not available in Rawlinsons were collected from the literature. For example, the cost data for pine saw log grades were collected from Island Specialty Timbers (IST 2011). The operational energy costs data were collected from Hayland (2011). Operational energy costs data included the local energy prices as well as its service charges.

In this study, Brisbane metropolitan's price data were used from Rawlinsons (Rawlinsons 2010). The year 2011 is considered as the base year for analysis. The prices were the average price for typical buildings. Construction and maintenance costs were calculated from data for material, labour and disposal costs. Labour costs included the standard set of labour constants. Disposal costs included the costs of removal of all debris, loading cost and waste management centre fees.

Future expenditure was calculated using the methodology discussed in Section 3.4.4. To verify the results of the future cost calculations, an experienced industry assessor (J. Morrissey [RMIT University] 2010, pers. comm., 8th March) was asked to check and verify the calculations.

4.6 MODELLING ASSUMPTION AND JUSTIFICATION

A set assumption was made, and simplifications were applied to build the LCA model. The LCA were conducted using a whole building and whole life cycle context, as discussed in Section 3.4.3. Details of assumptions and simplifications are described in this section.

4.6.1 Operational energy modelling assumption

In this case, the annual operational energy (MJ/m^2 per annum) for heating and cooling was estimated for continuous occupancy based on standard occupant behaviour for a four-person family. The living room areas were assumed air conditioned from 0700 to 2400 and the bedroom areas from 1600 to until 0900. The bath and en-suite areas were assumed to be excluded from any air conditioning.

It was assumed that mechanical air conditioning and natural ventilation operation are switched on automatically, so that the natural ventilation satisfies occupant thermal comfort. The thermostat settings for heating and cooling were based on the Protocol for House Energy Rating Software published by Australian Building Codes Board (ABCB 2006). Two components of cooling were distinguished. Cooling (latent) accounts for the energy required to reduce the humidity of the indoor air. Cooling (sensible) accounts for the energy required to reduce the air temperature. The lifetime operational energy was calculated from the annual energy multiplied by the house lifetime. It was assumed that the year round weather would be similar over the building lifetime.

To evaluate the environmental impact more accurately, the heating and cooling appliance's efficiency, and coefficient of performance (COP) were used. COP is measured by dividing the rate at which the heat is added or removed from a room (DEWHA 2008). This approach is described in the Australian Minimum Energy Performance Standard (AS/NZS 3823.2) for air-conditioners (Standards Australia 2011a). In this study, a ducted cooling system with a COP of 2.79 with 30% duct losses (equivalent to overall COP of 1.96) was used. The reason to choose COP of 2.79 is that it is the minimum energy performance standard (AS/NZS 3823.2) for air-conditioners used in Australian state (DEWHA 2008; Standards Australia 2011a). In addition, a ducted cooling system was chosen, as it is commonly used in the Brisbane climate (DEWHA 2008).

4.6.2 LCA modelling description, system boundary and assumption

In this study, the ISO 14044 guidelines for LCA were followed. A streamlined LCA approach was undertaken using PRé's *SimaPro* (version 7.3) LCA software. *SimaPro* is particularly suitable for the studies on Australian dwellings as it provides the Australian database AusLCI (Chen 2010; Newton et al 2009; Tharumaharajah & Grant 2006). The modelling system description, boundaries and assumptions are discussed below, along with justifications.

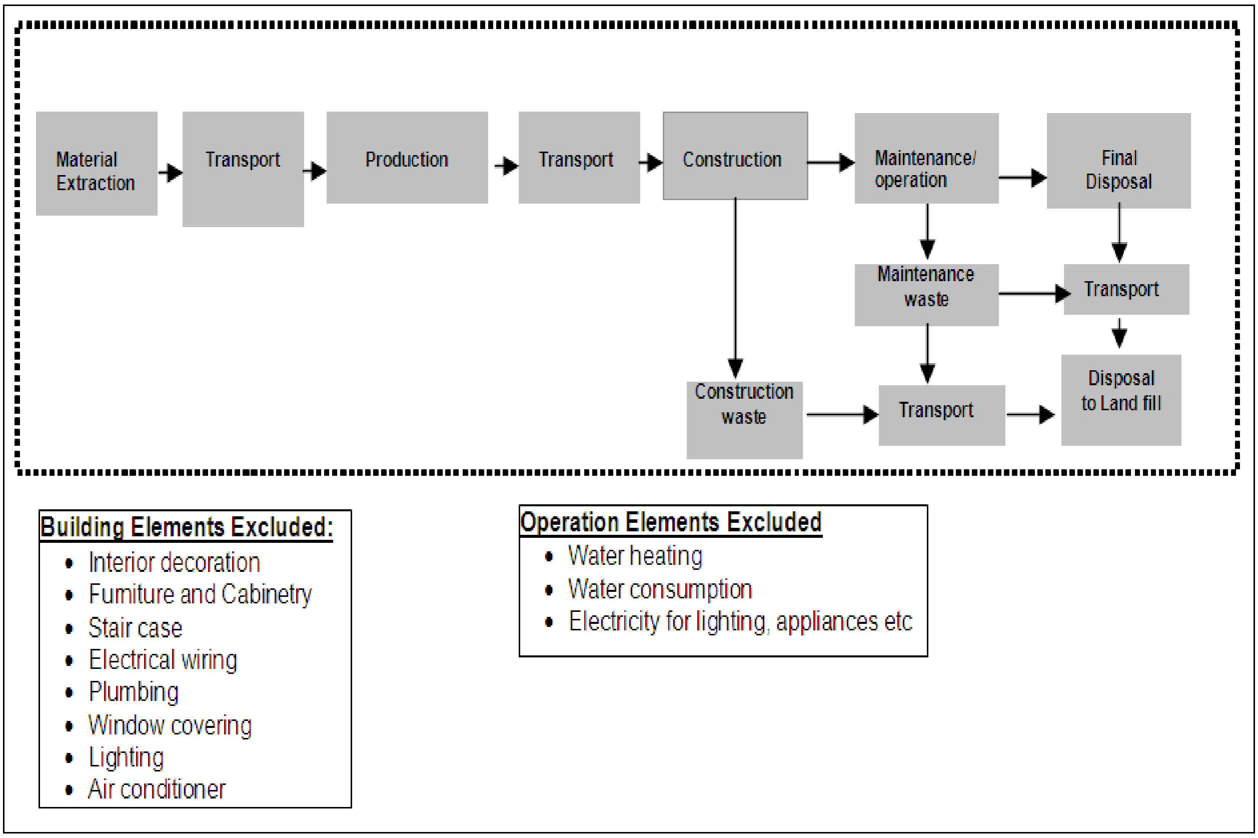
4.6.2.1 Goal and Scope

The goal of this LCA study is to estimate the life cycle environmental impacts of a case study house with modified building envelope designs. The functional unit of this LCA is the life cycle of one occupied residential dwelling over a fifty-year lifetime. The life cycle includes construction, operation, maintenance and disposal, with 101m^2 of usable floor areas. As discussed in Section 3.4.3.1, the goal and scope phase must identify the system boundaries and assumption to be made for LCA. The system boundaries of this LCA study are shown in Figure 4.4.

The system boundary **includes**:

- raw material extraction and production (i.e. steel plates, timber studs etc)
- manufacturing of building components (i.e. windows, timber floor)
- transportation from raw material extraction to part fabrication, to the construction site
- construction work at the building site, including excavation
- energy consumed during the operation phase
- maintenance and renovations
- demolition at the end of useful life
- transportation of demolished materials to landfill

Figure 4.4 : LCA system boundary



The system boundary **excludes**:

- technological improvements (i.e. reuse or recycling of building waste)
- interior decoration
- interior appliances energy and water consumption
- electrical wiring, plumbing
- furniture, built-in cupboards, sink and kitchen utensils

- vehicle and machinery in the temporary construction site
- urban planning infrastructure (i.e. roads, drive-way concrete and landscaping)

Technology improvements are certain to occur in the next 50 years in operation, maintenance and disposal, but these are difficult to predict. For simplicity, it was assumed that they affect each design equally. Hence, technology could be excluded from this study. House orientation and shape may have an effect on heating and cooling energy requirements but these have been evaluated extensively elsewhere (Crawford et al. 2011; Wang 2005). Hence, these were not a variable in this study. The house was modelled with its actual orientation (north facing) and shape.

4.6.2.2 LCA System assumptions

This section describes the LCA system assumptions used in this study. Table 4.11 shows the assumptions and scenarios used in some previous LCA studies.

Table 4.11 : A comparison of different LCA studies assumptions

Study	**Assumption type**				
	Life span	**Building types**	**Area**	**Geography**	**Functional unit**
Carre (2011)	50 years	single storey	200m^2	Australia	1m^2 usable floor
Rouwette (2010)	50 years	single storey	-	Australia	total house
Maddox & Nunn (2003)	60 years	single storey	127m^2	Australia	total house
Mithraratne & Vale (2004)	100 years	single storey	94 m^2	New Zealand	not specify
Nemry et al (2010)	40 years	varieties	various	Europe	total house
Ortiz et al (2010)	50 years	double storey	160m^2	Spain	1m^2 usable floor
Szalay (2007)	50 years	varieties	various	Hungary	total house
Adalberth et al (2001)	50 years	apartment	-	Sweden	usable floor area
Frenette et al (2010)	60 years	double storey	-	Canada	200m^2 usable wall
Kahhat et al (2009)	50 years	single-story	200m^2	USA	200m^2 usable wall
Lippike et al (2004)	75 years	double/single	190-200m^2	USA	total house
Blanchard & Reppe (1998)	50 years	double storey	2450ft^2	USA	total house

Lifespan of building: The life span of building is difficult to standardise, as discussed in Section 2.4.5. It depends on many factors. However, for modelling purposes a life span must be chosen even if this is considered arbitrarily (Carre 2011; Frenette et al 2010). In this study, the chosen life span (50 years) was consistent with other studies shown in Table 4.11. This assumption is also consistent with the guidance of Australian Building Code Board guidelines (ABCB 2006).

Functional unit: The functional unit of this LCA study is "per house" (life cycle of total house). This is also consistent with many studies shown in Table 4.11.

Maintenance: The maintenance schedules for elemental materials are shown in Table 4.12 as used in this and other studies. In the literature, the timing of a major renovation varies from 20 to 100 years, depending on the element type. For example, wooden claddings such as weatherboard may need to be replaced more often (ranging from 20 to 50 years) than brick (ranging from 50 to 100 years). As shown in Table 4.12, most components of the wall, floor, and ceiling elements are replaced after 25 years except for a few more durable elements that are replaced after 50 years or more. In this study, a major renovation was modelled after 25 years for all materials (except brick, concrete and timber framing for simplicity).

Table 4.12 : Maintenance schedules: literature and this study (years)

Type	Element	Australia & New Zealand			Europe		For This study
		Rouwette (2010)	Ding (2007)	Mithraratne (2001) (High/average/low)	Szalay (2007) (High/average/low)	Oswald (2003) (High/average/low)	
Major	Brick/Concrete	100	60	50;100;100	50;100;100	-	**50**
	Timber Frame	50	50	-	-	-	**50**
	Roof tiles	50	50	30;>100	40;60;100	-	**50**
	Doors	-	40	30;60;65	30;40;50	25;35;50	**50**
	Windows	-	40	30;60;65	30;40;60	25;35;50	**50**
	Insulation	50	50	50;60;75	30;40;60	-	**50**
	FC sheet	-	-	40;50;60			**25**
	Plaster render	25	25	50,60;75	20;25;40	20;25;35	**25**
	Weatherboard	-	40	20,30;40	-	25;35;50	**25**
	Timber floor	25	25	-	30;40;50	25;35;50	**25**
	Ceiling	25	25	-	30;40;60	25;35;50	**25**
	Plasterboard	25	25		35;50;100	25;35;50	**25**
	Ceramic Tiles	25	25	20;30;40	20;30;40	-	**25**
Minor	Repainting	10	10	6;8;10	10;15;25	6;10;25	**10**

The internal envelope materials (i.e. plasterboard, ceramic tiles, plaster render, timber floors and ceilings) were replaced during the major renovation. External claddings such as FC sheet, pine saw log and weatherboard were also replaced during major renovation. Brick and concrete have longer durability so no cladding replacement was considered during the major renovation.

Minor renovation includes repainting only. In the literature, there is a range of timing for repainting from every 6 to 25 years. In this study, the minor renovation was modelled at the median timing of 10 years, that is, four times over a 50 years lifetime.

Disposal: There are wide ranges of options for building materials at the end of life or final disposal. Building materials can be disposed of to landfill, reused or recycled. If materials are recycled or reused, there are some impacts associated with recovery and reprocessing. If materials are disposed to landfill, the main impacts associated with material are that it remains within the landfill for extended period, as well as transport to the landfill. Hence, the majority of building materials are disposed of to landfill (Ximenes et al 2008). Technology improvements are certain to occur in the next 50 years in disposal but these are difficult to predict. In this study, the assumption was made to dispose of all the building materials to landfill during construction, maintenance and at the end of life.

Disposal of timber to landfill is modelled as a reduction of GHG (CO_2 equivalent) emissions. Timber materials store a significant amount of carbon for more than 100 years (Carre 2011). Within the period of this study (50 years), the biogenic carbon within the timber is considered stored for the calculation of GHG emissions. Therefore, the GHG assessment of timber in landfill appears as a negative contribution to the total impact. Carre (2011) also used this approach in his recent study.

Transportation: In this study, the transport mode was by road using articulated truck. Construction materials were assumed to be transported 50km from the manufacturing gate to construction site. This distance is consistent with other studies (Cuellar-Franca & Azapagic 2012; Ortiz et al 2009; Rajagopalan et al 2010). A 28tonne load on 30tonne truck with a back haul ratio of 1.2 was used in this study, as consistently used in *SimaPro*. The back haul ratio is the fraction load of one-way trip distance.

In this study, the demolition wastes are transported for 30km from the dwelling to landfill site. This distance is consistent to recent studies (Cuellar-Franca & Azapagic 2012; Ortiz et al 2010).

4.6.2.3 *LCIA method*

As discussed in section 2.4.2.3, a wide variety of Life Cycle Impact Assessment (LCIA) methods is used in LCA. This study applied the Australian Impact Method with Normalisation including cumulative energy demand (CED). The reason to choose this method is that this LCIA method is a part of the Australian Life Cycle Inventory database, and it comprises a number of impact indicators relevant to Australian environmental issues (Carre 2011; Grant & Peters 2008). In addition, the indicators in this LCIA method are broadly consistent with best practice (Grant & Peters 2008). The impact categories include in this LCAI method are greenhouse gas (CO_2 equivalent), cumulative energy demand, water use, solid waste, acidification potential, eutrophication, land use, and photochemical oxidation potential. Only subsets of these impact categories were used in this study, discussed in next section.

4.6.2.4 *LCA Impact category indicators*

This study focussed mainly on four impact category indicators including greenhouse gas (GHG) emission, Cumulative Energy Demand (CED), water use and solid waste concerning as global and regional indicators. GHG and CED are global climate change indicators (Blanchard & Reppe 1998; Ortiz et al 2008; Rouwette 2010). Many LCA studies on buildings have focussed on GHG gas emission and CED as the main impact indicators (Blanchard & Reppe 1998; Ortiz et al 2008; Rouwette 2010). Hence, GHG and CED were selected as global indicators in this study.

The increasing demand for water insufficiency and lower rainfall makes water usage a prime interest in the Australian context. Solid waste is also a major focus in the Australian context. This is because the buildings produce 40% of waste going to landfill and increase air emission (GBCA 2012; Ximenes et al 2008) so this is a major concern for countries and government. Some state governments have goal to meet towards zero waste targets going to landfill (ZWSA 2004). Therefore, water use and solid waste were selected as regional indicators. The four impact indicators are discussed below.

GHG: GHG is the sum of all emissions over the life cycle, including CO_2 equivalent gases (i.e. carbon dioxide, nitrous oxide and methane). CO_2 equivalent GHG gases are also a commonly used reference standard for Global Warming Potential (GWP). A weighting factor was used to estimate single GHG emission. The weighting factors are given in section 2.4.2.3.

CED: The CED or life cycle energy is the sum of material extraction to end of life management. It includes the raw material extraction, pre-construction processes, and the energy used in on-site construction, maintenance, operation and disposal stages.

Water use: Water usage is calculated by summing the water used in the unit process considered in this LCA model.

Solid waste: Solid waste is the sum of solid waste from production of material waste mainly during construction, maintenance and disposal.

Two other impact indicators (biological diversity and land use) were considered of significance in this study, but they were not included in analyses. This was because suitable quality inventory data is limited in regional database such as AusLCI (Hamilton et al 2008).

4.6.3 LCC modelling assumption

As discussed in section 3.4.4, future costs (i.e. operation, maintenance and demolition cost) were calculated using an inflation rate of 3% and a discount rate of 6%.

For simplicity, the following elemental costs were not included in this analysis, as these were assumed to be similar in all scenarios and do not affect the study outcomes: initial settlement costs (i.e. land, property taxes, and other fees), plumbing, electrical wiring, furnishings, cabinetry, staircases, air conditioner and interior decorations. The resale value was not included in this analysis due to lack of valid and reliable data.

The detailed results for the case study house are discussed in the next section.

4.7 RESULTS OF THE CASE STUDY HOUSE

4.7.1 Operational energy results for case study house

The case study house was analysed using the building rating software *AccuRate*. The methodology was described in Section 3.4.2. The case study house was estimated to have a rating of 3.6 stars equivalents. The annual operational energy requirements for heating were estimated to be 18.2 MJ/m^2.annum and for cooling, 63.3 MJ/m^2.annum. The energy loads are multiplied by the conditioned floor area and building life span to estimate the full life cycle energy input. This was then used as data input to the LCA software *SimaPro*. In this case, the LCI data was adjusted based on typical energy source and appliances efficiency, as discussed in Section 4.6.1.

4.7.2 LCA results for the case study house

The LCA results of four selected life cycle impact category indicators (GHG, CED, water use and solid waste) are shown in Table 4.13, showing three significant figures. These indicators were chosen as they are the most frequently cited in the literature or are of prime interest in a regional (i.e. Australian) context, as discussed in Section 4.6.2.4.

Table 4.13 : Selected life cycle impact category indicators of the case study house

Impact indicator	Unit	Construction	Operation	Maintenance	Disposal	Total
Greenhouse gas (GHG)	Tonne CO_2	26.0	48.0	6.43	-4.21	76.2
	Percentage	34.0%	63.0%	8.43%	-5.52%	100
Cumulative Energy Demand (CED)	GJ	380	560	127	13.0	1080
	Percentage	35.1%	51.9%	11.7%	1.20%	100
Water use	kL (H_2O)	1940	65.4	1090	0.29	3100
	Percentage	62.6%	2.11%	35.2%	0.01%	100
Solid waste	Tonne	3.86	1.63	4.95	70.3	80.8
	Percentage	4.78%	2.02%	6.13%	87.0%	100

In broad terms, the results show that impact categories vary with life stage. The categories of GHG and CED are dominated by the construction and operation stages, water usage by the construction and maintenance stages, and solid waste is dominated by the end of life management or disposal stage. Hence, the relationship between the impact categories and life stages is complex. This suggests it is important to characterise the multiple life stages when selecting an optimum design, depending on the impact categories of interest. For the category of GHG, CED, water use and waste impacts, the detailed results at each life cycle stage are discussed below. Comparison with the literature is given in Section 4.7.3.

GHG: Construction and operation dominates for the category of GHG emissions: with 34 and 63%, respectively. More detail is shown in the process tree in Figure 4.5 and Appendix 4.G (2% limits). The “2% limits” means an element that contributes less than 2% to the total impact is excluded from the picture. The roof construction is omitted, as the scale limit in the process trees was set to 2%, and it contributed less than 2%. Hence, the thicker the pathway, the higher the contribution.

Figure 4.5: Process tree for the case study house (GHG, 2% limit)

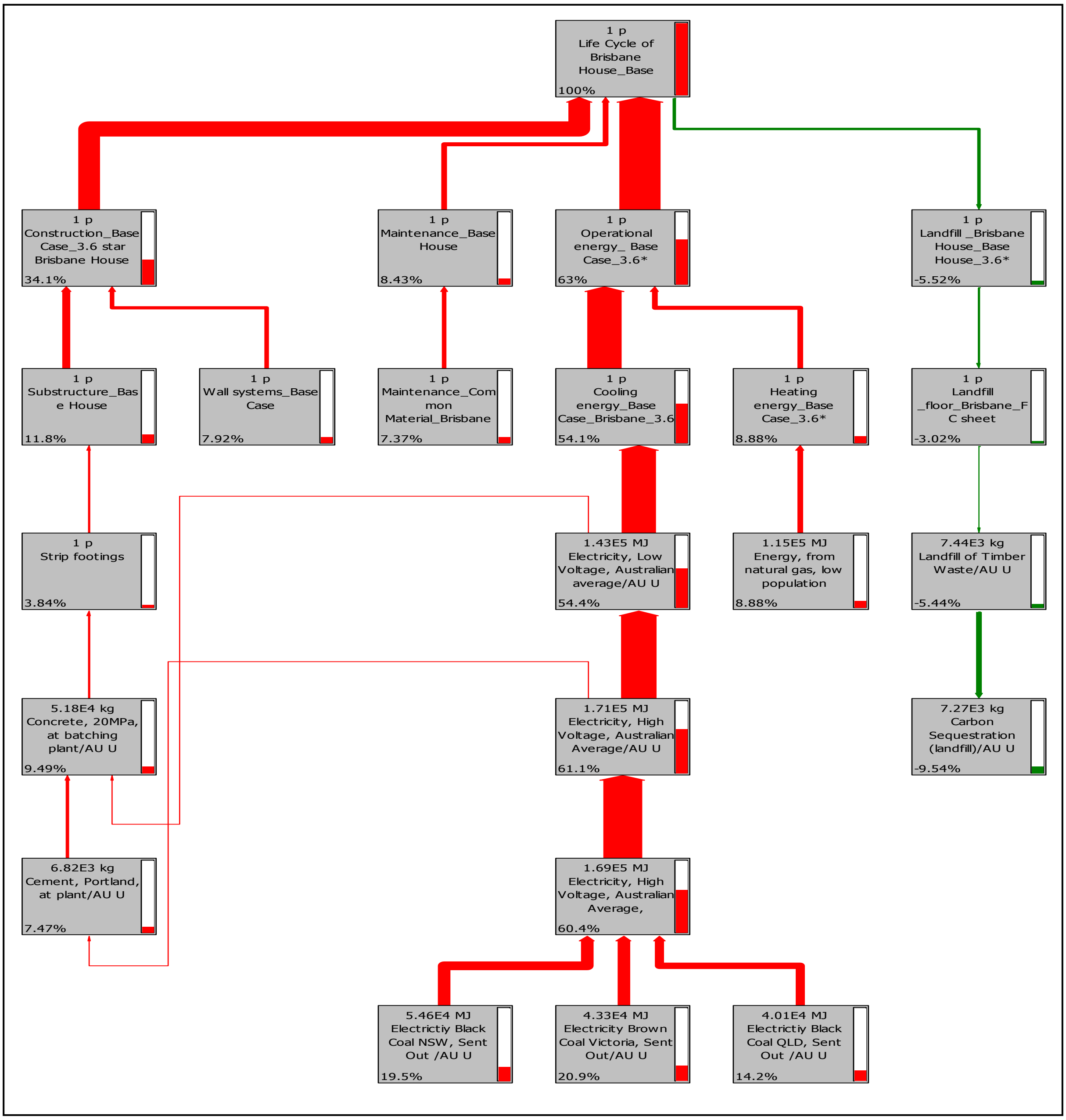


Figure 4.5 shows the main contributors to the 34% of GHG impacts that occurred during the construction phase were substructure (12%) and wall systems (8%). These impacts include raw material extraction, material processing, assemblage manufacture as well as disposal of onsite construction waste.

Figure 4.5 also shows that the main contributors to the 63% of GHG impacts that occurred during the operations life stage were heating and cooling energy. This operational energy is as expected, as these were the only two energy usages included in the system boundary of the LCA model for operation life phase. The large amount of cooling (54%) compared to heating (9%) reflects that the modelled climate is sub-tropical. In Brisbane, more cooling is needed than heating, as the summer is hot and the winter is mild. Hence, the majority of total GHG over the whole life cycle in a climate like Brisbane is due to cooling energy.

Figure 4.5 shows that the main contributors to the 8% of GHG impacts that occurred during the maintenance life stage were mainly from material replacement during major renovation (7%). More detail is shown in the process tree in Appendix 4.H (2% limits). Materials replaced include internal wall and ceiling plasterboard, floor and wall tiles and timber floors.

Figure 4.5 shows that the main contributors to the interesting negative impact (-6%) of GHG impacts that occurred during the disposal life stage, were from land filling of timber. Burying timber in the anaerobic conditions of landfill is considered carbon sequestration (Carre 2011; Ximenes et al 2008), so the reported impact is negative. This high number reflects the assumption made in this study that landfill is the only waste treatment method at construction, maintenance and disposal stage.

CED: For the category of CED, again construction and operation dominate, with 35 and 52% respectively (Table 4.13). More detail of the impacts is shown in the process tree in Figure 4.6. Elements such as steel reinforcement and disposal are omitted from Figure 4.6, as the scale limit in the process trees was set to 2%, and these individually contributed less than 2%. The box title in Figure 4.6 '1 p life cycle of Brisbane' should read '1 p life cycle of Brisbane House_base' due to a limitation in Simapro.

Figure 4.6: Process tree for the case study house (CED, 2% limit)

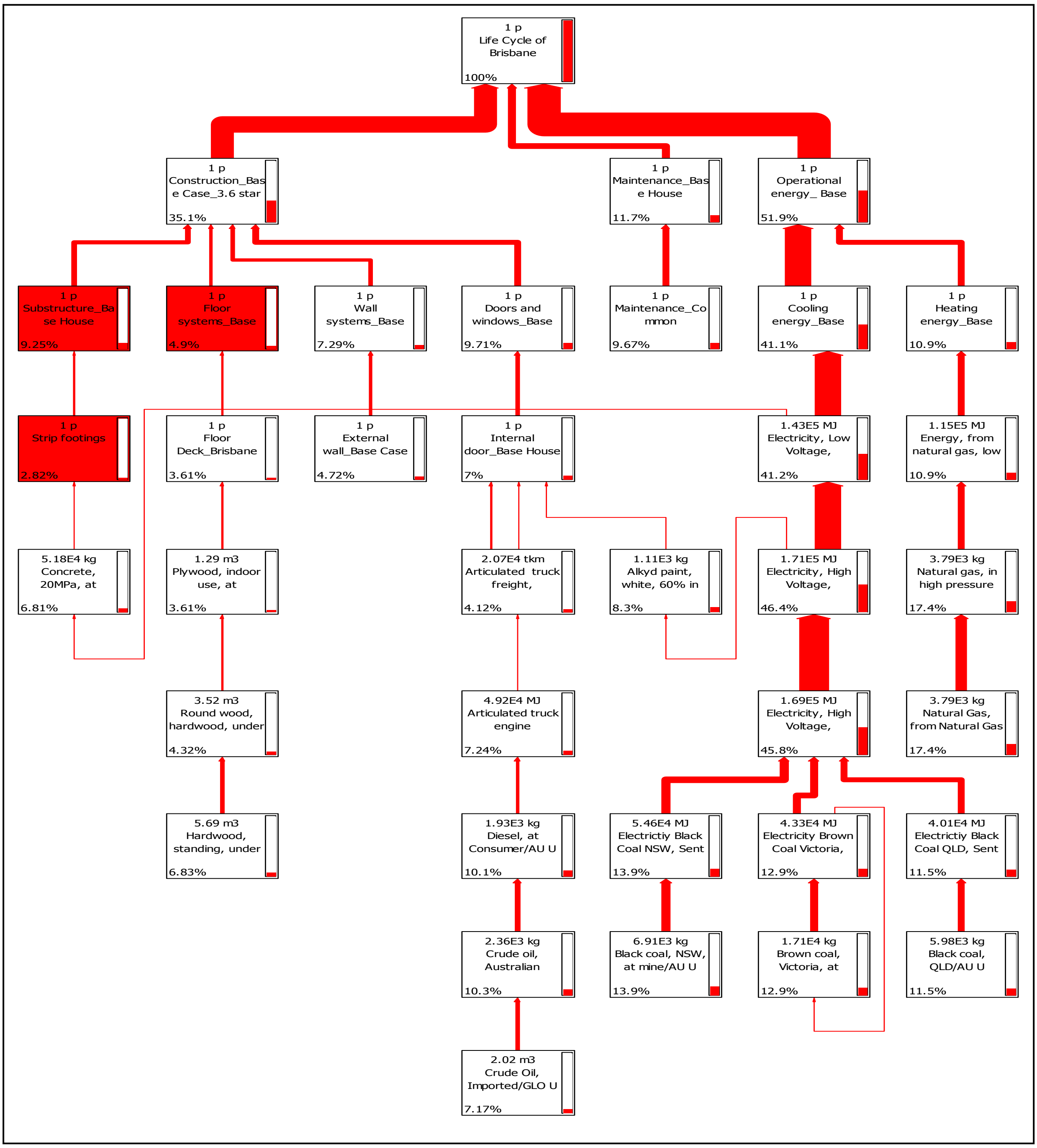


Figure 4.6 shows that the main contributors to the 35% of CED that occurred during the construction phase were substructure (9%), floor (5%), wall systems (7%) as well as doors and windows (10%).

Figure 4.6 also shows that the main contributors to the 52% of CED impacts that occurred during the operation life stage were heating (11%) and cooling (41%). This is as expected as discussed for GHG.

Figure 4.6 also shows that the main contributors to the 12% of CED impacts that occurred during the maintenance life stage were from common material replacement (10%) during major renovation, as for GHG.

For the disposal life stage, the main contributor to the 1% of CED impacts that occurred was disposal to landfill at the end of life. It also included the impact for transportation to transfer the dismantled materials to landfill. There is no carbon sequestering benefit for CED. This is the major difference between GHG and CED impact categories.

Hence, the figures for CED are slightly higher than for GHG for life stages other than disposal. The overall trend is similar to GHG, except for disposal.

Water use: For the category of water use, the main contributions were from the construction phase, 63%, and maintenance, 35%, (Table 4.13). Full details are given in Appendix 4.I. The high water use components in both the construction and maintenance phases are the ceiling and wall plasterboard, timber floors and external wall claddings. The contribution of the construction phase is higher than maintenance because there are several high water use components not replaced during maintenance including foundations concrete, timber frame and roof tiles.

Solid waste: For the category of solid waste, the disposal contributed the majority of the impact (87%). This is as expected, as the assumption was made in this case study that the only end of life scenario is landfill.

The small contribution (5%) of construction reflects the model assumption used in this study that there is only 5% onsite construction wastage during construction, as discussed in Section 3.4.1. The similar small contribution (6%) of maintenance reflects disposal to landfill of the replaced materials including wall claddings, plasterboard and floor covering.

In summary, an LCA model of a residential dwelling allows its environmental impact to be quantified. Different categories are dominated in different life stages: GHG and CED are dominated in construction and operation stage, water use by construction and maintenance, solid waste by disposal.

The results are compared with the literature in the next section.

4.7.3 Comparison of LCA results for the case study house with other studies

There have been numbers of LCA studies on residential buildings in Australia and elsewhere, as discussed in Sections 2.4.5. As mentioned, region specific life cycle inventory exist in LCA studies for housing, so that a comparison of a region specific study is the most appropriate. In this section, a comparison with the results of recent Australian LCA studies of residential buildings is made.

Most LCA studies on buildings focus on CED and GHG gas emission as the main impact indicators for climate change (Blanchard & Reppe 1998; Ortiz et al 2008; Rouwette 2010) so there are a good number of studies to review for a comparison. Only few recent studies have also included water use and solid waste, so the potential for comparison is much more limited for the impacts of water use and solid waste.

The Australian studies are summarised in Table 4.14 below.

Table 4.14 : Case study house results comparison with other LCA studies of residential buildings

Study	System description and assumptions	GHG	CED
Case study house	Brisbane climate, 3.6 star rating, 50-year lifetimes; includes the effect of heating/cooling, excludes the effects of interior decorations, lighting, and other household appliances; assumes 70% appliances efficiency for heating; assumes a coefficient of performances (COP 2.75) and 30% duct losses for cooling; disposal includes dismantling of the original construction materials and their transport to the final destination to land fill	• construction 34% • operation 63% • maintenance 8% • disposal -5%	• construction 35% • operation 52% • maintenance 12% • disposal 1%
Carre (2011)	Australian climate (Brisbane, Sydney, and Melbourne), 5 star rating, 50-year lifetime; excludes interior decorations and household appliances; assumes a COP of 3.5 with 20% ducting loss for cooling; assumes 70% efficiency for heating. disposal phase includes dismantling of the original construction materials and their transport to recycling and landfill.	• construction 31–43% • operation 53-68% • maintenance 4-6% • disposal -1 to -5%	• construction 31–44% • operation 52–64% • maintenance 5-6% • disposal (-1 to -3%)
Rouwette (2010)	Australian climate (Newcastle, Melbourne and Brisbane), 50-year lifetime; excludes interior decorations and household appliances and major renovation; star rating and appliances energy efficiency not specified; disposal phase includes only transportation impact for construction materials to recycling and land filling	(Newcastle climate only) • construction 47% • operation 51% • disposal (2%)	-not specified
Iyer-Raniga & Wong (2012)	Australian climate (Victoria), various 0.8 to 5.1 star ratings, 100-year lifetime; excludes interior decorations and household appliances; includes appliances efficiency for operational energy; assumes 65% appliances efficiency for heating; assumes a COP of 3 and no duct losses for cooling; disposal phase includes dismantling of all the materials to landfill, with no carbon sequestration or material energy recovery from landfill	• construction, maintenance and disposal ranged 7-24% • operation 76-93%	• construction, maintenance and disposal 4-18% • operation 82-96%
Maddox & Nunn (2003)	Australian climate, 60-year lifetime; includes interior decorations, heating/cooling, lighting and household appliances; excludes major renovations, the appliances efficiency not specified	• construction 3-5% • operations 90%	-

GHG: For GHG, the findings of this case study house are most similar to Carre (2011). The results for case study house fall within the range reported by Carre for the construction, operation and disposal phase, and are similar for maintenance. This reflects the many similarities in assumptions in this study.

Other studies show less similarity. Some report high GHG levels in construction (Rouwette 2010) and some lower (Maddox & Nunn 2003; Iyer-Raniga & Wong

2012). The reverse is true for operation. Rouwette (2010) reports lower and Iyer-Raniga & Wong (2012) report higher than this case study house.

These variations reflect major differences between assumptions made for this case study and these previous studies. For example, Rouwette (2010) excluded GHG emissions for major renovations while maintenance was 8% of the total emission for this case study. Therefore, for Rouwette's study, construction, and operation would be proportionally higher. Rouwette did not specify the star rating of the building in his study so the relative contribution of construction and operation cannot be compared to the case study house.

Iyer-Raniga & Wong (2012) assumed a 100 years lifetime compare to 50 years for the case study house, so operations would be expected to the higher as shown.

CED: For CED, the findings of this case study house are most similar to the findings of Carre (2011). Both the construction and operation are within the range of findings of Carre's study, and maintenance and disposal are similar, as for GHG. Other studies found significantly different results for CED attributed to differences in assumptions as different as above (Table 4.14).

Likewise, Maddox & Nunn (2003) included energy usage of lighting and household appliances beyond heating and cooling, so operations would be expected to proportionally higher.

Water Use: The results are similar to the published literature on the effect of water usage in residential house design. In this study the main contributions were the construction (63%) and maintenance (35%), which is in a similar ratio to that reported by Crawford (2011) and Crawford & Pullen (2011) (2:1) and similar to the figures reported by Carre (2011) (72% for construction and 20-36% for maintenance). Carre (2011) also found operation contributed 1–3% to water use, similar to this case study's findings of 2%.

Solid waste: There are also few reports in the literature on the effect of solid waste impact. Findings for the disposal phase appeared only in recent studies. A comparison of this study with Carre (2011) is shown in Table 4.15.

Table 4.15 : Case study house results comparison with LCA studies of residential buildings by Carre (2011)

Study	Construction	Operation	Maintenance	disposal
This case study	5%	2%	6%	87%
Carre (2011)	12-22%	2-6%	13-28%	54-67%

The results are not similar. The differences are again attributable to the differences in assumption both recycling and landfill for waste disposal: this study used landfill only.

In summary, the results for this case study house are similar to or within the range found in several other LCA studies. This supports the validity of the LCA model for the case study house. Differences may be attributed to different assumptions about maintenance, disposal as well as building life span. It can also be attributed to the inclusion of the effect of appliances efficiency, COP, water heating and lighting.

4.7.4 Comparison of the case study LCC with the literature

The LCC of the case study house are summarised in Table 4.16. Full details of the LCC model were discussed in Section 3.4.4. The LCC is quite low for this case study house at just below $210,000, as the costs for land and interior decoration, wiring or plumbing were not included. Construction and maintenance contributed the most (88%) to the life cycle cost. Operation and disposal contributed relatively little.

Table 4.16 : Life cycle cost ($) of the case study house

House Name	Construction	Operation	Maintenance	Disposal	Total
Base Case	129,000	20,000	54,000	5,600	209,000
Percentage	61.7%	9.74%	25.9%	2.69%	100

The construction costs are quite low, at just below $130,000. This is lower than the results obtained from a recent Australian study by McLeod & Fay (2011), who estimated the cost of a 4 star, two bedroom standard Adelaide, single storey at approximately $150,000. The difference may be attributed to the differences in house design, location and material and labour price as well as the assumptions that this study was modelled 3.6 star rating designs in Brisbane.

The following section compares the results for the case study house with the relevant literature in terms of LCC. Table 4.17 shows the LCC results for several residential buildings studies.

Table 4.17: Comparison of LCC results for this study with the literature studies

Study	Context, assumptions	Construction (% of total)	Operation (% of total)	Maintenance (% of total)	Disposal (% of total)
This case study house	Australian house, estimates costs in present value; assumes 6% discount rate and 50-year lifetime; includes construction operation, maintenance and disposal; excludes land price, interior decoration, wiring, and plumbing	62%	10%	26%	3%
Zacharia (2003)	Canadian house, estimates costs in present value, assumes (2, 4, 6, 8 %) discount rate and 35 years lifetime, includes construction, operation and disposal, excludes maintenance	88%	11%	-not specified	2%
Sterner (2002)	Swedish house, estimates costs as the total present value, assumes a 2.5% discount rate, 60 year lifetime	56%	20%	22%	2%
Johansson & Oberg (2001)	Swedish house, estimates costs as the total present value, assumes a 2.5% discount rate, 60-year lifetime; includes periodic maintenance and care taking	50-60%	23-34%	25-37%	-not specified
Blanchard & Reppe (1998)	US house, estimates cost in present value, assumes a 4% discount rate, 50-year lifetime; includes accumulated mortgage (land and construction cost), operational energy costs and maintenance or improvement costs; not discussed disposal cost separately	68-79%	3-9%	20-22%	-not specified
Bejrum et al (1986)	Swedish house, estimates costs in present value, assumes a 4% discount rate, 50-year lifetime; includes construction, operational costs and maintenance; not discussed disposal cost separately	65%	10%	25%	-not specified

The initial cost (material and construction) and maintenance life stages contributed the bulk of costs for all studies. The fraction of costs for construction, maintenance, operations and disposal were broadly similar. The differences may be attributed to the differences in price data and assumptions. All the literature studies are from regions other than Australia. This limits the direct comparability.

In summary, for the category of life cycle cost, the results for the case study house show trends similar to several previous studies of residential house designs. This supports the validity of this LCC model.

4.8 SENSITIVITY ANALYSIS OF CASE STUDY HOUSE

A sensitivity analyses should be undertaken in LCA and LCC to assess model robustness in terms of data uncertainty. For LCA, the sensitivity to life span, transportation distance and maintenance scenarios was evaluated. For LCC, sensitivity to discount rate was studied. The analysis was carried out for the case study house model only.

4.8.1 Sensitivity analysis of the LCA model of the case study house

4.8.1.1 Life span

This study assumed a 50 years life span. This assumption was based on the median life span used in the literature (Section 4.6.2.2) but the actual life span of a building may be shorter or longer. In this sensitivity analysis, the effect of life span was analysed by substituting a longer timeframe of 100 years into the LCA model. In this analysis, it was assumed that there would be no significant benefit from any retrofits or energy efficiency upgrades during this period. The operational energy was modeled as annual heating and cooling energy demand multiplied by the number of years. Maintenance was modeled as a minor renovation every 10 years and a major renovation every 25 years. Hence, operational energy and maintenance increase in proportion to the life span.

Table 4.18: Influence on LCA outcomes of building life span: whole life cycle

Impact Category	Life Span		
	50years	100years	Differences (%)
GHG (Tonne CO2)	76.2	131	71.4
CED (GJ)	1080	1760	63.7
Water Use (kL)	3100	4260	37.3
Solid Waste (Tonne)	80.8	87.3	8.15

Table 4.18 summarises how the LCA impact categories are affected by changes in the building life span. The results show that the variation of life span significantly influences the outcome for the majority of impact categories. For example, the life cycle GHG and CED is increased by 71% and 64% respectively, when the building

lifetime was increased to 100 years from 50 years. These findings are comparable to an Australian study: Iyer-Raniga & Wong (2012) reported that the life cycle GHG and CED increased by 47% and 46% respectively, when the building lifetime was increased to 100 years from 50 years. The differences may be attributed to annual heating and cooling requirement for Melbourne and Brisbane climates. For example, the 5-star homes must achieve annual heating/cooling loads of less than: 149MJ/m² for Melbourne and 55MJ/m² for Brisbane climate (Carre 2011), so that these variations influence the study outcome for 100 years lifespan. Iyer-Raniga & Wong considers in Melbourne climates: this study in Brisbane.

Table 4.19: Sensitivity of LCA results to building life span: life cycle phases

Impact indicator (Units)	**Life span (years)**	**Construction**		**Operation**		**Maintenance**		**Disposal**	
		Total	**%**	**Total**	**%**	**Total**	**%**	**Total**	**%**
GHG (Tonne)	50	26.0	34.1	48.0	63.0	6.43	8.43	-4.21	-5.52
	100	26.0	19.9	96.0	73.5	12.8	9.83	-4.21	-3.22
CED (GJ)	50	378	35.1	560	51.9	127	11.7	13.0	1.20
	100	378	21.4	1120	63.4	253	14.3	13.0	0.73
Water Use (kL)	50	1940	62.7	65.4	2.11	1090	35.1	-0.29	0.01
	100	1940	45.6	130	3.07	2190	51.3	-0.29	0.01
Solid waste (Tonne)	50	3.86	4.78	1.63	2.02	4.95	6.13	70.3	87.0
	100	3.86	4.42	3.26	3.74	9.90	11.3	70.3	80.5

Table 4.19 illustrates how the impacts change over the building life phases if the life span is increased. The effect of increasing life span is to reduce the contribution of the construction and disposal phases whilst that of operation and maintenance increases. This is expected because in the model both operation and maintenance increase in proportional to life span, while construction and disposal are independent of life span increases. Hence, the relative contributions of different life stages changes with life span. In a broader context, these findings are in line with one Australian study (Iyer-Raniga & Wong 2012).

For the categories of GHG and CED, the contribution of the construction and operation life phases changes significantly with change in lifespan. The results for GHG and CED are reduced approximately 14% in the construction phase, and increased approximately 10% in the operation phase. These findings may be comparable to Australian study: Carre (2011) found 33% variation for GHG in construction. These variations may be attributed: Carre considers sensitivity analysis for building lifetime 75 years, and this study 100 years. The changes in maintenance and disposal are not significant as these life phases make a relatively small contribution to total GHG and CED.

For the category of water use, the contribution of the construction and maintenance phases changes significantly with change in lifespan. The contribution of the construction life phase reduced by 17% whilst maintenance increased by 16%. This is due to the replacement of components produced with high water usage in the maintenance phase (e.g. plasterboard) and maintenance increases in proportion to life span, while construction is independent of lifespan. Water usage in the operation and disposal phases is negligible so any changes are not significant. For the category of solid waste, the contribution of the maintenance phase increased the most (8%) with change in life span. This is due to more cycles of renovation in the maintenance stage over the longer lifespan. However, none of the changes was significant.

Overall, the effects of GHG, CED and water use were changed significantly with the change of lifespan. Since compare with another house designs, these changes do not affect the overall relative conclusions, when compare with another similar house designs.

In summary, as lifespan increases, construction and disposal contribute proportionally less, and operation and maintenance contribute proportionally more, because construction and disposal occur only once per lifetime, independent of the lifetime length. Overall, the outcomes for three LCA impact categories (GHG, CED, and water usage) show significant changes with lifespan that may not affect the overall relative conclusions, when compare with another similar house designs.

4.8.1.2 Transportation distance

In this study, it is assumed that construction materials are transported 50km from the manufacturing gate to construction site using an articulated 30t truck. The demolition wastes are also transported for 30km from the construction site to landfill using a garbage transit (rigid truck), as discussed in Section 4.5.2. In this sensitivity analysis, the effect of transportation distance was analysed by substituting a longer distance of 100km into the LCA model. This substitution is assumed to have a more significant effect than others, such as transport mode.

Table 4.20: Influence on LCA outcomes of transportation distance: whole life cycle

Impact Category	Transport Distance		
	50km	**100km**	**Differences (%)**
GHG (Tonne CO2)	76.2	84.8	11.2
CED (GJ)	1080	1200	11.8
Water Use (kL)	3100	3100	0.08
Solid Waste (Tonne)	80.8	80.8	0.01

Table 4.20 summarises how the LCA impact categories are affected by changes in transportation distances. The results show that variation in transport distance has a significant effect on GHG and CED, by around 11%. Water use and solid waste show no sensitivity to transportation distance.

Overall, outcomes from two LCA impact categories (GHG and CED) are affected significantly by transportation distance. Therefore, the model is sensitive to transportation distance for construction and disposal.

4.8.1.3 Maintenance scenario

In this study, an "average" maintenance schedule was assumed: the frequency of a minor renovation (repainting) was every 10 years, and the frequency of a major renovation (replacement of plasterboard, ceramic tiles, plaster render, timber floors, ceilings and weatherboard) was every 25 years. These assumptions were based on the median frequency of maintenance used in the literature, as described in Section 4.6.2.2. However, the actual maintenance may be lower or higher or not at all. In this sensitivity analysis, a low maintenance scenario was evaluated. In low maintenance, most of the elements are not changed at all. It is assumed that in a major renovation, which occurs every 25 years, only the plasterboard is replaced, and repainting is carried out every 25 years.

Table 4.21: Influence on LCA outcomes of maintenance scenario: whole life cycle

Impact Category	Maintenance scenario		
	Average	Low	Differences (%)
GHG (Tonne CO2)	76.2	70.6	7.36
CED (GJ)	1080	970	9.50
Water Use (kL)	3100	2030	34.4
Solid Waste (Tonne)	80.8	75.8	6.13

Table 4.21 summarises how the LCA impact categories are affected by changes in maintenance scenario. The results show that variations in maintenance schedule has a significant influence on water use, by 34%. GHG, CED and solid waste show less sensitivity to maintenance schedule, and are not significantly affected.

Overall, outcomes for water usage are significantly affected by low maintenance scenario. Szalay (2007) found that CED is reduced 5% by low maintenance: similar to this study. However, Szalay did not report on water usage. This analysis suggests that the model is sensitive to maintenance scenario for water usage only.

4.8.2 Sensitivity analysis of the LCC model of the case study house

In this study, LCC was calculated from initial construction costs and future costs for operation, maintenance and disposal, as described in section 3.4.4. The future costs were discounted to present value using a discounting rate of 6%. This is the discount rate recommended by the Department of Infrastructure (2005). In this sensitivity analysis, the effect of discount rate on LCC was analysed by substituting a lower discount rate (3%) into the LCC model. This substitution was chosen as it is assumed to have a more significant effect than others, such as energy cost, carbon tax or material cost.

Table 4.22: Influence on LCC results of discount rate: whole life cycle

Description	**Construction**	**Operation**	**Maintenance**	**Disposal**	**Total**
Discount rate 6%	$ 129,00	$ 20,000	$ 54,000	$ 5,600	$ 209,000
Life phase contribution	61.7 %	9.74 %	25.9 %	2.70 %	100 %
Discount rate 3%	$129,000	$39,000	$110,000	$18,000	$296,000
Life phase contribution	43.4 %	13.1 %	37.3 %	6.20 %	100 %

Table 4.22 summarises how LCC is affected by discount rate over the life phases of the building cycle. The results show that the future cost increases as discount rate decreases, as expected. Changes in discount rate have a significant effect on total costs, as well as operation, maintenance and disposal costs, and on the contribution

of different life phases. Total life cycle costs increased significantly, by 42%. Operation, maintenance and disposal costs all increased significantly higher, by approximately 90%, 100%, and 220%, respectively. While the contribution of construction decreases significantly (by about 18%), construction remains the major contributor to total costs (43%). The contributions of operation, maintenance and disposal all increased.

Overall, LCC is affected by the changes in discount rate significantly, as discount rate affects the future operation, maintenance, and disposal costs as well as the total life cycle costs. Therefore, this LCC model is sensitive to discount rate. However, when the same rate is applied to each design, the discounting rate does not effect the overall conclusions, as similar to Zacharia (2003).

In summary, the LCA and LCC models are sensitive to changes in the major assumptions. Several LCA impact categories (especially GHG and CED) vary significantly with changes in building lifespan and transportation distance. The impact of water usage varies significantly with the changes in maintenance scenarios. If the life span, transport distance and maintenance frequency is increased, all impacts increase. As construction and disposal are fixed, their contribution to overall impact reduces, while that of operation and maintenance increases proportionally. The choice of discounting rate influences the LCC significantly as well as the contribution from different life stages. Future costs increase when discount rate decreases. The contribution of construction decreases while that of operations, maintenance and disposal all increases. As the LCA and LCC models are sensitive to the main assumptions in the model, this means that making correct assumptions is important to achieving robust model outcomes. In this study the same assumptions will be applied to each design. Each design is likely to be affected by model assumptions in a similar way, so the model assumptions are unlikely to affect the overall conclusions about ranking of designs.

4.9 SUMMARY

In summary, this chapter describes how the case study was selected. It describes all aspects of the house designs from data description to modelling input, in conjunction with modelling assumptions and simplifications. It also describes the data quality and modelling requirements along with rationale and justification. The results for the case study house are similar to or within the range found in the published literature. This supports the validity of the LCA and LCC model for the case study house. The sensitivity analyses show that the LCA and LCC models are sensitive to changes in major assumptions but this is not expected to change the overall ranking of designs, when one design is compared with another similar design, as all designs will be affected in a similar way.

The results for the house designs with modified wall, roof and floor assemblages are presented in the next three chapters. Chapter 5 represents the detailed results for the houses with various wall assemblages. The results for houses with various roof and floor assemblages are presented in Chapters 6 and 7, respectively.

CHAPTER 5: WALL ASSEMBLAGE DESIGN

Introduction; Effect of wall assemblage design on LCA and LCC; Comparison of results for house designs with different star rating; Graphical analysis of all the house designs; Summary

5.1 INTRODUCTION

In this chapter, the results of the LCA and LCC of all wall assemblage designs are presented. The results were derived using the model and assumptions described in Chapters 3 and 4. The effects of selected alternative wall designs were evaluated. The case study house was used as the base case for all the alternative wall assemblage designs. In this chapter, only wall assemblage designs are varied while floor and roof assemblages are kept the same. The results are analysed for the whole building on a whole of life cycle basis. The results for alternative roof and floor assemblage designs are presented in Chapters 6 and 7.

The alternative wall assemblage designs presented in this chapter have variations in external wall cladding, insulation type and thickness, and air gap thickness and position. Each design is varied such that it achieves a chosen star rating (in increments from 3.6 to 3.9 star), for example, by adding slightly thicker insulation. Five exterior wall claddings are selected, typical of the Australian building industry. These claddings are brick, concrete (autoclave aerated concrete block), fibro-cement sheet, pine saw logs and weatherboard. The effect of these selected alternatives are analysed in terms of their economic and environmental impact. The detailed results for the alternative selected wall assemblage designs are presented first. Then, the optimum wall designs are identified using a graphical approach.

5.2 EFFECT OF WALL ASSEMBLAGE DESIGN ON LCA AND LCC

This section reports how different assemblage designs of the exterior walls affect the environmental impacts and life cycle costs over the various house life stages. The chosen wall assemblage designs in the various scenarios were selected from those available in *AccuRate*, as this tool is commonly used in the Australian building industry, as discussed in Section 3.4.2. Five wall assemblage designs were made with five cladding types. Different operational energy performances (star ratings) were achieved.

The assemblage designs with the same star rating were then compared. This approach was taken, as it is an effective way to compare wall assemblage designs made from very different materials. This approach is similar to that undertaken in one Australian study by Carre (2011) and another US study by Lippke et al (2004). The star rating in this study was varied from 3.6 to 3.9 stars, so the wall assemblage designs could be assessed over a range of operational performance levels. The lower limit of 3.6 star designs was chosen, as this was the rating for the actual case study house. The upper limit of 3.9 stars was chosen, as this was the maximum rating possible for several of the wall claddings. The limiting factors for all the designs were either best practice approach or minimum BCA performance requirements. This is in line with the recent Australian study by Iyer-Raniga & Wong (2012).

The lifetime and the total annual operational energy requirements of each wall assemblage is used to calculate the total operational energy for a house, and this is used as input data for the LCA model. The environmental and cost impacts of each design are then compared against a number of criteria to find the optimum.

5.2.1 Results for the 3.6 star rating house designs - wall assemblages

The case study house was modelled in *AccuRate,* and found to have a star rating of 3.6 stars. Therefore, a 3.6 star rating was the first rating level chosen to assess the various wall cladding options. Each alternative wall assemblage was designed with various wall claddings with or without insulation to achieve a rating of 3.6 stars (where feasible). Three alternative claddings were modelled (weatherboard, concrete, fibre cement). Brick and pine saw logs designs are omitted from the following section as they provided 3.7 star without any insulation for this particular case study house, i.e. there were no feasible designs at 3.6 stars.

5.2.1.1 Operational energy results

The operational energy requirements of the houses with 3.6 star wall designs are shown in Table 5.1. Full details for each of the wall assemblages are given in Section 4.3.2.

Table 5.1: Rated energy requirements of the 3.6 star rating houses - wall assemblages

Annual Energy Requirements (MJ/m^2.annum)	Base Case	Concrete	FC sheet	Weatherboard
Heating	18.2	17.9	17.6	16.4
Cooling-sensible	46.0	45.0	45.1	46.9
Cooling-latent	17.3	17.3	17.2	17.8
Total Energy	81.5	80.2	79.9	81.1

The results show that the annual operational energy requirements are very similar for all the designs, as expected, because the designs were constrained to achieve the same star rating.

5.2.1.2 LCA results

The results for the selected life cycle impact category indicators are given in Table 5.2. In broad terms, all the designs have the same type of impacts at different life stages, similar to the case study house. The same impact categories are dominated by the same life cycle stages, as for the case study house. The category of GHG emission and CED are dominated by the construction and operation phases, water use by the construction and maintenance phases, and solid waste is dominated by the disposal phase. Hence, the life stage with the environmental impact depends on the choice of impact category. Therefore, different life stages need to be considered when optimising new designs.

Table 5.2: LCA results for the 3.6 star rating house designs - wall assemblages

GHG (Tonne)					
House Name	Construction	Operation	Maintenance	Disposal	Total
Base Case	26.0	48.0	6.43	-4.21	76.2
Concrete House	28.5	47.3	5.97	-4.12	77.6
FC Sheet House	26.1	47.2	6.43	-4.21	75.5
Weatherboard House	25.1	48.3	5.00	-4.70	73.7
Average	26.4	47.7	5.96	-4.31	75.7
Percentage (%)	**34.1**	**62.9**	**7.87**	**-5.69**	**100**
Cumulative Energy Demand (GJ)					
House Name	Construction	Operation	Maintenance	Disposal	Total
Base House	378	560	127	13.0	1080
Concrete House	395	551	120	13.8	1080
FC Sheet House	380	549	127	13.0	1070
Weatherboard House	370	558	118	13.3	1060
Average	381	554	123	13.3	1070
Percentage (%)	**35.6**	**51.7**	**11.5**	**1.24**	**100**
Water Use (kL)					
House Name	Construction	Operation	Maintenance	Disposal	Total
Base House	1940	65.4	1090	-0.29	3100
Concrete House	1960	64.3	1080	-0.66	3090
FC Sheet House	1940	64.3	1090	-0.29	3090
Weatherboard House	1930	66.8	1080	-0.36	3080
Average	1940	65.2	1090	-0.40	3090
Percentage (%)	**62.7**	**2.10**	**35.1**	**0.01**	**100**
Solid Waste (Tonne)					
House Name	Construction	Operation	Maintenance	Disposal	Total
Base House	3.86	1.63	4.95	70.3	80.8
Concrete House	4.05	1.61	5.53	76.8	87.9
FC Sheet House	3.86	1.61	4.95	70.4	80.8
Weatherboard House	3.85	1.67	3.63	69.0	78.2
Average	3.91	1.63	4.76	71.6	81.9
Percentage (%)	**4.77**	**1.99**	**5.82**	**87.4**	**100**

GHG: On average, construction and operations contributed the bulk 97% of the emissions. The results for disposal are negative, as disposal has a GHG credit, as there is carbon sequestration in the land filling of wood. The level of emissions across the whole life cycle did not vary significantly: it varied by only 5% from best to worst wall assemblage designs. The weatherboard house had the lowest and concrete house the highest emissions, due to higher emissions for concrete in the construction phase, as expected.

For the category of GHG, all designs contributed very similar emissions in the construction phase, except for the concrete assemblage design. Concrete design had a 13% higher GHG emission than the lowest emission (weatherboard). This is because concrete has high GHG emissions during manufacturing, whilst timber (weatherboard) manufacturing is a relatively low energy process.

The operational energy requirements were similar for all designs, as their walls were designed to have the same star rating. Operational energy is the major contributor to GHG. Hence, the variation in total emissions for the whole life cycle was relatively small.

The contribution of maintenance to GHG is relatively small (6%) but it varied significantly with design, by 28% from best to worse. The lower GHG emissions for some designs were attributed to the higher amount of timber in some designs such as weatherboard, which provided a higher GHG credit.

The contribution of disposal to GHG was similar for all designs. All the designs have a negative value, indicating a positive impact on the environment. This is because all designs contain timber frames so each has a credit at disposal, as timber in landfill is modelled as a carbon sequester. The weatherboard house also had exterior timber cladding so this contributed to the slightly higher credit, similar to the results for maintenance.

In summary, for the category of GHG, overall, the designs have a variation of only 5% from best to worse. The concrete design had a significantly higher contribution (13%), in the construction phase and the weatherboard design had the lower contribution (28%), in the maintenance phase.

CED: For the category of CED, construction and operation contributed almost all (87%) of the total energy consumptions. There was no significant impact of wall assemblage design. CED across the whole life cycle did not vary significantly: it varied by only 2% from best to worst assemblage designs. The level of emissions during construction also did not vary significantly: it varied by only 7% from best to worst wall assemblage designs.

Water use: For the category of water use, on average, construction and maintenance contributed almost all (98%) of the total use. There was no significant impact of wall assemblage design. This is due to the commonality between the designs of the high water use components, that is, wall and ceiling plasterboard, timber floor, and external wall cladding and paint.

Solid waste: For the category of solid waste, on average, only the life stage of disposal contributed a significant impact (87%). Across the whole life cycle, the solid waste varied significantly (by 13%) from best to worst house design. The weatherboard house had the lowest impact, and the concrete house the highest. This may be attributed to the lower volume of materials used in a weatherboard house compared to a concrete house.

In summary, for the categories of GHG, CED and water use, all the 3.6 star rating house designs had similar environmental impacts. Only the concrete clad house contributed significantly higher GHG emissions in the construction phase as well as significantly higher solid waste at the disposal phase. The weatherboard-clad house had the lowest impact for several categories, attributed to use of materials produced with less energy intensive processes and the sequestration of carbon at disposal.

5.2.1.3 LCC results

Table 5.3 shows the life cycle costs of the 3.6 star house designs.

Table 5.3: Life cycle cost ($) of the 3.6 star rating house designs -wall assemblages

House Name	Construction	Operation	Maintenance	Disposal	Total
Base Case	129,000	20,000	54,000	5,600	209,000
Concrete House	137,000	20,000	54,000	5,900	217,000
FC sheet House	129,000	20,000	53,900	5,600	209,000
Weatherboard House	130,000	20,000	55,000	5,600	211,000
Average	131,000	20,000	54,000	5700	211,000
Average %	62.0	9.56	25.7	2.68	100

The total costs are quite low, around $210,000. The cost does not include land price or interior decoration, wiring or plumbing. The construction costs are lower by $20,000 than those reported in a recent Australian study by McLeod & Fay (2011) for a 2-bedroom single storey standard house. This may be attributed to the difference in star rating of the houses designs (0.4 stars) as well as differences in house design, location and assumptions of material, exclusions of elements and labour costs. On average, construction contributed most to the total cost (62%), followed by maintenance (26%). The contribution from operation and disposal is relatively small.

Table 5.4: Difference (%) in LCC of the 3.6 star rating house designs-wall assemblages

House Name	Construction	Operation	Maintenance	Disposal	Total
Base Case	0%	0%	0%	0%	0%
Concrete House	6%	0%	1%	5%	4%
FC Sheet House	0%	0%	0%	-1%	0%
Weatherboard House	1%	0%	2%	-1%	1%

Table 5.4 shows the percentages difference in life cycle costs for the 3.6 star rating house designs compared to the case study house (base case). The result shows that all differences are less than 10%, so none is considered significant. Total LCC of the best and worst design are within 4% of the base case. Costs are similar because the different designs have a high commonality of material used in construction and maintenance, and the same star rating so operation costs are similar.

As 62% of costs come from construction (Table 5.4), these costs are a prime focus of cost minimisation in the building industry (Sterner 2002). Only 10% of costs come from operations, so there may be little incentive for householders to invest in reducing operations costs compared to construction costs. A wider range of designs will be investigated, to assess if significant savings can be produced with better design.

5.2.1.4 Discussion

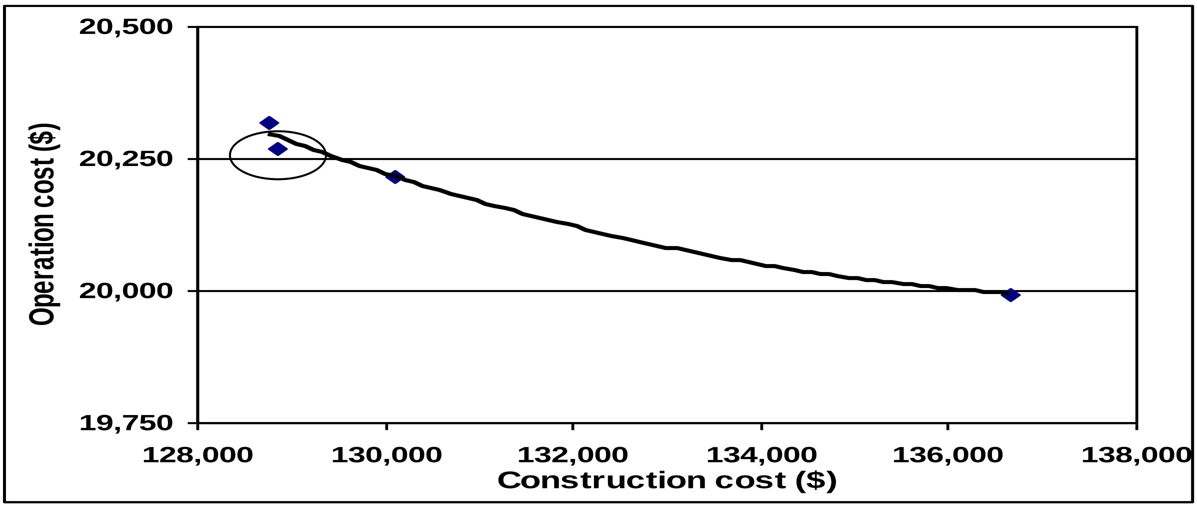
Questions such as "What are the best 3.6 star assemblage designs?" can be answered by use of a single or multi-objective evaluation approach. In the following discussion, first a single then a multi-objective evaluation approach is used to identify the significant or set of optimum design for the houses with 3.6 star wall designs. A graphical approach is used in both single and multi-objective cases.

For a product such as a residential building, the major stakeholder is likely to be the owner. The owner may identify one criterion as more important than any other and then, single objective evaluation is a very efficient approach to identify the best design. To compare alternative designs, it is appropriate for stakeholders in the product or service to be identified and consulted about the ranking of relevant performance criteria (Frenette et al 2010).

Using a single objective approach, the design can be “evaluated” for only one objective function at a time. For example, the owner (householder or builder) may wish to minimise costs. Then one outcome from this study might be that all the house with 3.6 star wall designs are equally good in terms of cost, as the variation was only 4% from highest to lowest, depending on the sensitivity of the owner to cost variation. If the owner wishes to minimise operational energy, the outcome is also that all the house designs are equally good. This is as expected, because operational energy was constrained to the same annual energy per square meter of housing in order to achieve the same star rating.

The owner may be interested in minimising more than one variable. The demand for low economic and environmental cost is growing (Asadi et al 2012; Wang 2005; Zacharia 2003) so this scenario will become more common. In this scenario, single objective minimisation cannot be used: a multiple objective approach should be used.

Figure 5.1: Operation and construction costs: 3.6 star rating house designs -wall assemblages



Using a multiple objective approach, two or more objective functions can be minimised at the same time. If only two variables are to be minimised, this can be done by plotting one variable against the other in a graph. This is shown in Figure 5.1 for operational energy cost and construction cost. The dataset for the 3.6 star rating designs shows a high degree of variability, but it appears that there is one slightly better-the 3.6 star rating FC sheet house (ringed in Figure 5.1). It has lower operational and construction costs than the best-fit line to the data, so is tentatively identified as the “best” of the designs modelled.

If a broader approach is taken, multiple objective functions can be considered, such as the whole of life cycle assessment across a range of impact categories as well as life cycle costing. Figure 5.2 show a graphical approach for multi (five) objectives, four life cycle environmental impact indicators and life cycle cost. Normalised data are shown: the actual value for any impact is divided by the minimum value. The minimum value was identified using single objective evaluation. In this way, categories with different units can be compared on the same scale. A similar approach was undertaken in several previous studies (Azapagic & Clift 1999; Hawe & Sykulski 2008; Konak et al 2006). The best design has values closest to unity with minimal spread: that is, all objective function variables are minimised. The best house design will have a good performance across a range of categories, with ratios close to unity.

Figure 5.2: Normalised LCC and LCA impacts for the 3.6 star rating house designs - wall assemblages

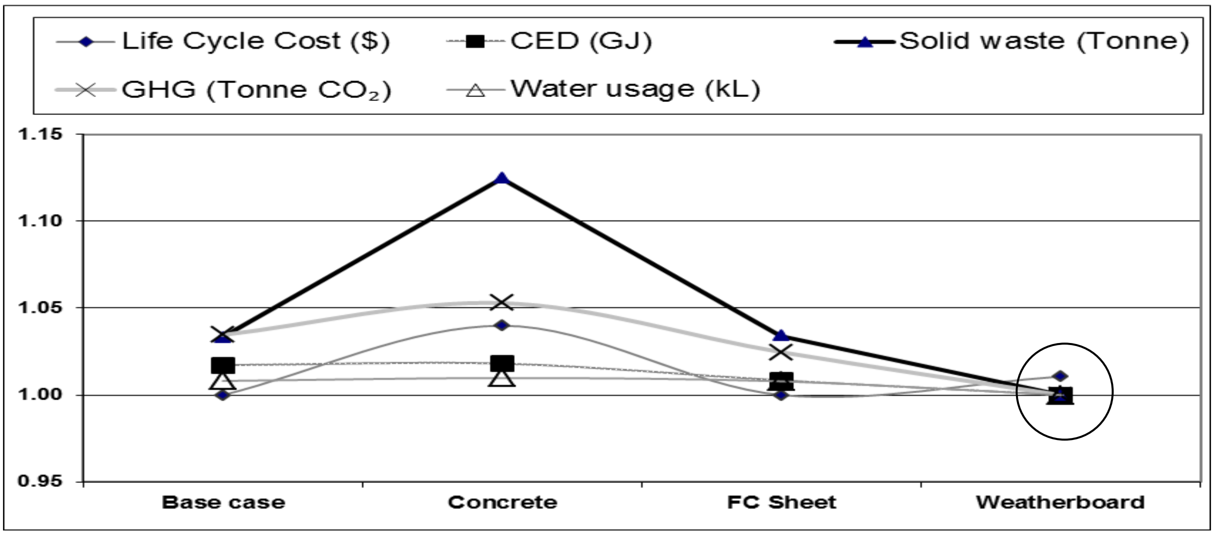


Figure 5.2 shows that there is one design that performs best on a broad range of categories (ringed): the weatherboard-clad house, although the differences to FC sheet and base case are small (less than 10%). This is a contrast to the single objective approach, where all designs were equally good, and the multi objective approach considering only two variables, where only the FC sheet house was identified as the best design. This shows that the “best” design depends on evaluation approach and which objective functions are considered. The limitations to this graphical approach can be overcome by using Mathematical Programming (MP) model for optimisation

(Azapagic & Clift 1999; Hawe & Sykulski 2008; Konak, Coit & Smith 2006). The results using MP modelling are presented in Chapter 8.

In summary, the optimum wall cladding design depends on the number and type of objective functions considered as well as the approach. FC sheet is found to be the best when just cost is optimised. Weatherboard is best when multiple objectives are considered.

Houses with a range of star ratings (3.7, 3.8 and 3.9 stars) are considered in the next sections. The comparisons of all the houses with 3.6 to 3.9 star wall designs are discussed in Section 5.3 to assess to what extent the optimum design depends on the star rating.

5.2.2 Results for the 3.7 star rating house designs - wall assemblages

5.2.2.1 Operational energy results

House designs with a 3.7 star rating and various wall assemblages are compared in this section. The annual energy requirements for these designs were modelled in *AccuRate* and are shown in Table 5.5. Full details of the assemblage designs were given in Section 4.3.2. Five claddings are modelled including brick, concrete, FC sheet, pine saw log and weatherboard.

Table 5.5: Rated energy requirements of the 3.7 star rating house designs - wall assemblages

Annual Energy Requirements (MJ/m^2.annum)	Brick	Concrete	FC sheet	Pine Saw Log	Weatherboard
Heating	17.2	17.1	16.1	17.1	15.2
Cooling-sensible	44.7	44.5	44.2	44.1	45.8
Cooling-latent	17.4	17.2	17.1	17.4	17.7
Total (Energy)	79.3	78.8	77.4	78.6	78.7

The result shows that the operational energy requirements were similar, as expected, as for the 3.6 star designs, as the designs were constrained to achieve the star rating. The heating and cooling energy requirements are used as input data to the LCA model.

5.2.2.2 LCA results

Results for selected life cycle impact categories are shown in Table 5.6 for the 3.7 star rating house designs with various wall assemblages.

Table 5.6: LCA results for the 3.7 star rating house designs -wall assemblages

GHG (Tonne)					
House Name	Construction	Operation	Maintenance	Disposal	Total
Brick House	29.0	46.9	5.96	-4.09	77.8
Concrete House	28.5	46.6	5.97	-4.12	76.9
FC Sheet House	26.2	46.1	6.43	-4.21	74.5
Pine Saw log House	24.8	46.5	3.43	-7.99	66.7
Weatherboard House	25.3	47.1	5.00	-4.70	72.6
Average	26.8	46.6	5.36	-5.02	73.7
Percentage (%)	**36.3**	**63.2**	**7.3**	**-6.81**	**100**
Cumulative Energy Demand (GJ)					
House Name	Construction	Operation	Maintenance	Disposal	Total
Brick House	408	545	119	14.3	1090
Concrete House	395	541	120	13.8	1070
FC Sheet House	381	534	127	13.0	1050
Pine Saw log House	366	540	117	14.2	1040
Weatherboard House	373	542	118	13.3	1050
Average	384	540	120	13.7	1060
Percentage (%)	**36.3**	**51.0**	**11.3**	**1.30**	**100**
Water Use (kL)					
House Name	Construction	Operation	Maintenance	Disposal	Total
Brick House	1950	64.1	1080	-0.64	3090
Concrete House	1960	63.7	1080	-0.66	3090
FC Sheet House	1940	63.5	1090	-0.29	3100
Pine Saw log House	1930	63.5	1080	-0.36	3070
Weatherboard House	1930	65.6	1080	-0.36	3080
Average	1940	64.1	1080	-0.46	3080
Percentage (%)	**62.8**	**2.07**	**35.1**	**-0.01**	**100**
Solid Waste (Tonne)					
House Name	Construction	Operation	Maintenance	Disposal	Total
Brick House	4.06	1.60	5.53	85.1	96.3
Concrete House	4.05	1.59	5.53	76.8	87.9
FC Sheet House	3.87	1.59	4.95	70.4	80.8
Pine Saw log House	3.84	1.59	4.96	72.0	82.4
Weatherboard House	3.86	1.64	3.63	69.1	78.2
Average	3.94	1.60	4.92	74.7	85.1
Percentage (%)	**4.62**	**1.88**	**5.78**	**87.7**	**100**

In broad terms, the results show trends similar to the results of 3.6 star rating house designs. The different impact categories are dominated by different life stages. The categories of GHG and CED are dominated by construction and operation, water usage is dominated by construction and maintenance, and solid waste is dominated by the disposal phase.

GHG: For the category of GHG, on average, construction and operation contributed the most (99%) to the total emissions. Across the whole life cycle, the level of emissions varied significantly (by 17%) from best to worst house design. The pine saw log clad house design had the lowest, and brick and concrete had the highest GHG emissions.

The differences in emissions are mainly during the construction phase, where the brick house had 17% higher emissions than the pine saw log house. This reflects the energy intensive manufacturing process used for bricks. The operation phase was similar for all designs. This was expected, as all the designs have the same star rating, hence similar operational energy needs. In maintenance, GHG showed significant variations between designs. The difference from best to worst was very high, about 90%. This is partly attributed to the high contribution of GHG credit from pine saw log replacement. Disposal also showed significant variations between designs. The designs that contain more timber have a credit at the disposal phase as timber in landfill was modelled as a carbon sequester. The difference from best to worst was very significant (around 95%), similar to maintenance.

CED: For the category of CED, on average, construction and operation contributed the most (87%) of the energy used. CED across the whole life cycle was similar for all designs: it varied only 5% from best to worst house design. Only CED in the construction phase showed a significant variation: the brick house had 12% higher CED than the pine saw log design. This result is different to the 3.6 star rating designs, as different wall claddings were included in the two set of designs. Both brick and pine saw logs designs could not be included in the 3.6 star rating as without insulation, they exceeded a 3.6 star rating. The results for the operation, maintenance and disposal phases were similar for all designs. In CED there is no carbon sequestering benefit in disposal, so the results are different to GHG, where timber-cladding designs have a benefit of carbon sequestering.

Water use: For the category of water use, construction and maintenance contributed the most (88%), as for 3.6 star designs. The high contribution of these two life phases is due to the use of assemblages manufactured with high water use components (i.e. wall and ceiling plasterboard, roof tiles and external wall claddings) for both construction and the major renovation during maintenance. Overall, the water use was similar for all wall assemblage designs, as for 3.6 star rating designs.

Solid waste: For the category of waste impact, on average, the disposal contributed the most impact (88%), as expected. Across the whole life cycle, it varied significantly (by 23%) from best to worst house design. The results for construction, operation and maintenance stages were similar for all designs, and these life phases do not contribute significantly to waste, similar to the results for the 3.6 star rating house designs. For the category of waste impact, the weatherboard house was the best design.

In summary, for the houses with 3.7 star designs, the best design depended on the categories in question. For GHG emission, pine saw logs cladding yielded the best design; for CED, all the designs were similar except in the construction phase where pine saw log cladding was again the best; for water use, all the designs were similar; for solid waste, weatherboard was the best design. Again, the "best design" depends on the category. The differences between best and worst designs were higher for the 3.7 than the 3.6 star rating house designs: this was attributed to inclusion of a wider variety of wall claddings in the 3.7 star designs.

5.2.2.3 LCC results

The life cycle costs of the 3.7 star rating house designs with various wall assemblages are shown in Table 5.7.

Table 5.7: Life cycle cost ($) of the 3.7 star rating house designs: wall assemblages

House Name	Construction	Operation	Maintenance	Disposal	Total
Brick House	136,000	20,000	54,000	5,700	216,000
Concrete House	137,000	20,000	54,000	5,900	217,000
FC sheet House	130,000	19,000	54,000	5,600	209,000
Pine logs House	152,000	19,600	66,000	5,600	243,000
Weatherboard House	131,000	20,000	55,000	5,600	212,000
Average %	**62.6**	**8.94**	**25.8**	**2.59**	**100**

On average, construction contributed the most to the total cost (63%), followed by maintenance (26%). Operation and disposal had a relatively small contributions (of 9% and 3% respectively), similar to the 3.6 star rating house designs. The construction costs are quite low, around $135,000, except for one, the pine saw logs house, which has a significantly higher cost. Pine saw logs are a more expensive cladding material than the other types.

Table 5.8: Difference (%) in LCC for 3.7 star rating house designs – wall assemblages

House Name	Construction	Operation	Maintenance	Disposal	Total
Base Case	0%	0%	0%	0%	0%
Brick House	5%	-3%	1%	1%	3%
Concrete House	6%	-3%	1%	5%	4%
FC sheet House	1%	-5%	0%	0%	0%
Pine saw logs House	18%	-4%	22%	0%	16%
Weatherboard House	2%	-3%	2%	-1%	1%

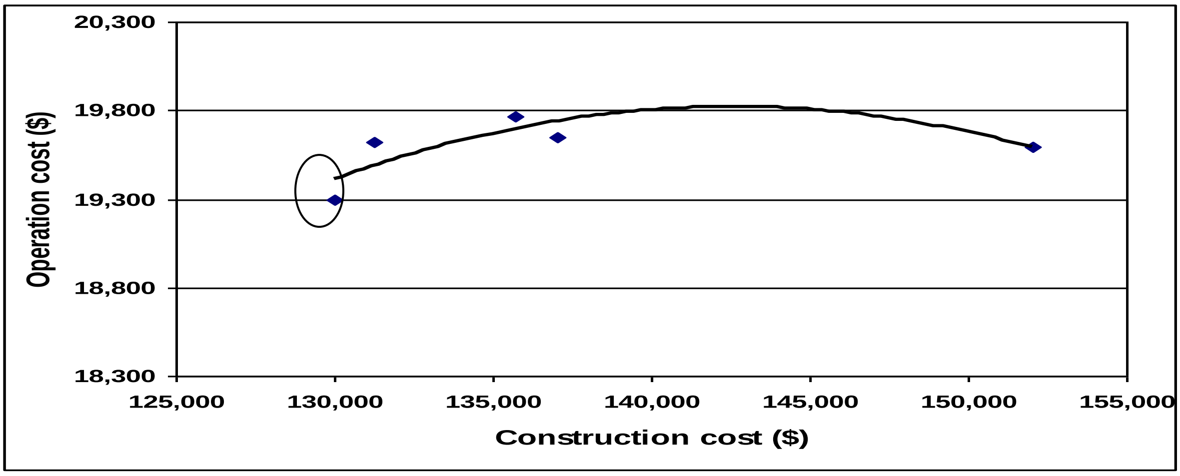
Table 5.8 shows the % difference in life cycle costs for the 3.7 star rating house designs with various wall assemblages. The results show that most of the houses cost a similar amount (within 4% of the base house) except for the pine saw logs design, which has a significantly higher cost (by 16%). The higher price of pine saw logs than other external wall claddings increases the construction and maintenance costs significantly (by 18% and 22% respectively). Operation and disposal costs are very similar among all 3.7 star designs.

In summary, the construction and maintenance phases dominate the LCC, as for the 3.6 star rating designs. Total costs are similar for all designs, except for the pine saw logs house design, due to higher cost of pine saw log cladding. Operation and disposal costs are similar for all designs.

5.2.2.4 Discussion

The wall assemblage designs are analysed in this section using a multi-objective evaluation approach, first with just two variables, then with multiple variables. Figure 5.3 shows a multi-objective (two-variable) approach for operation and construction costs.

Figure 5.3: Operation and construction costs of the 3.7 star rating house designs - wall assemblages



The figure shows that the best house design is readily identified as the FC sheet house, as this has both lower operation and construction costs.

Figure 5.4: Normalised LCC and selected LCA categories of the houses with 3.7 star rating -wall assemblages

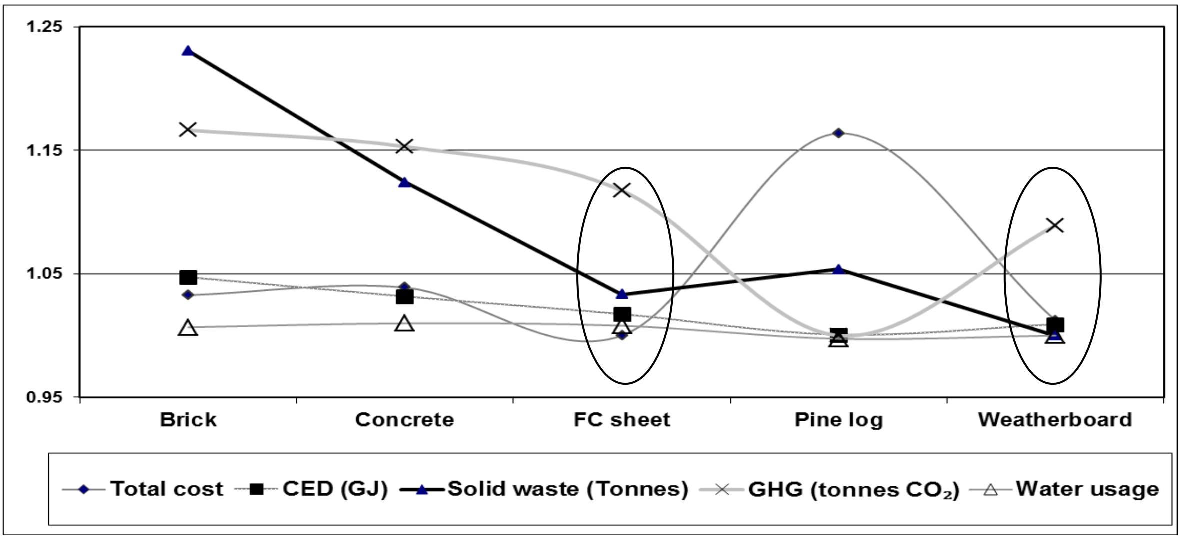


Figure 5.4 shows a multi-objective approach for the houses with 3.7 star wall-designs, showing normalised values for LCC and the four environmental impact indicators. It shows that there are two designs that perform well on a broad range of categories: the FC sheet and weatherboard house designs (ringed).

In summary, overall, for the 3.7 star rating designs, if only operation and construction costs are considered, there is only one best house design. However, if multiple variables are considered, then there are two good designs. This again shows that identification of the best building design depends on the number of variables considered, as discussed for the 3.6 star rating designs.

Houses with 3.8 and 3.9 star ratings are considered in the next sections.

5.2.3 Results for the 3.8 star rating house designs - wall assemblages

5.2.3.1 Operational energy results

This section presents results for the 3.8 star rating house designs with various wall assemblages. The same wall claddings are used, as for the 3.7 star rating houses. The annual energy requirements modelled in *Accurate* are shown in Table 5.9. The details assemblage designs were given in Section 4.3.2.

Table 5.9: Rated energy requirements for the 3.8 star rating house designs - wall assemblages

Annual Energy Requirements (MJ/m^2.annum)	Brick	Concrete	FC sheet	Pine saw Log	Weatherboard
Heating	15.5	15.4	15.4	15.4	14.2
Cooling-sensible	44	43.6	42.8	43.8	44.4
Cooling-latent	17.2	17.0	16.9	17.2	17.6
Total (Energy)	76.7	76.0	75.1	76.4	76.2

The result shows that the operational energy requirements were very similar for all designs, as for the houses with 3.6 and 3.7 star wall designs. This is as expected, as the designs were constrained to achieve the same star rating. The LCA results are discussed in the next section.

5.2.3.2 LCA results

A summary of LCA results for selected impact category indicators for the 3.8 star rating house designs with various wall assemblages are given in Table 5.10. In broad terms, the results show that different impact categories are dominated by different life stages, similar to the 3.6 and 3.7 star rating designs.

Table 5.10: LCA results for the 3.8 star house designs - wall assemblages

GHG (Tonne)					
House Name	Construction	Operation	Maintenance	Disposal	Total
Brick House	29.0	46.9	5.96	-4.09	77.8
Concrete House	28.5	46.6	5.97	-4.12	76.9
FC Sheet House	26.2	46.1	6.43	-4.21	74.5
Pine Saw log House	24.8	46.5	3.43	-7.99	66.7
Weatherboard House	25.3	47.1	5.00	-4.70	72.6
Average	26.8	46.6	5.36	-5.02	73.7
Percentage (%)	**36.3**	**63.2**	**7.27**	**-6.81**	**100**
Cumulative Energy Demand (GJ)					
House Name	Construction	Operation	Maintenance	Disposal	Total
Brick House	408	545	119	14.3	1090
Concrete House	395	541	120	13.8	1070
FC Sheet House	381	534	127	13.0	1050
Pine Saw log House	366	540	117	14.2	1040
Weatherboard House	373	542	118	13.3	1050
Average	384	540	120	113.7	1060
Percentage (%)	**36.3**	**51.0**	**11.3**	**1.30**	**100**
Water Use (kL)					
House Name	Construction	Operation	Maintenance	Disposal	Total
Brick House	1950	64.1	1080	-0.64	3100
Concrete House	1960	63.7	1080	-0.66	3110
FC Sheet House	1950	63.5	1090	-0.29	3100
Pine Saw log House	1930	63.5	1080	-0.36	3070
Weatherboard House	1930	65.6	1080	-0.36	3080
Average	1940	64.1	1080	-0.71	3090
Percentage (%)	**62.8**	**2.07**	**35.1**	**-0.01**	**100**
Solid Waste (Tonne)					
House Name	Construction	Operation	Maintenance	Disposal	Total
Brick House	4.06	1.60	5.53	85.1	96.3
Concrete House	4.05	1.59	5.53	76.8	87.9
FC Sheet House	3.87	1.59	4.95	70.4	80.8
Pine Saw log House	3.84	1.59	4.96	72.0	82.4
Weatherboard House	3.86	1.64	3.63	69.1	78.2
Average	3.94	1.60	4.92	74.7	85.1
Percentage (%)	**4.62**	**1.88**	**5.78**	**87.7**	**100**

GHG: For the category of GHG, on average, construction contributed 36%, operations 63%, maintenance 7% and disposal -7% of the emission. The emissions varied significantly across the whole life cycle, by 17% from best (pine saw log) to worst design (brick and concrete). The differences in emissions were mainly during the construction phase, where the brick house emitted 17% higher emissions than the pine saw logs house. This again reflects that brick manufacturing requires energy intensive process. The operation phase was similar for all designs. This was expected, as all the designs have the same star rating, so have similar operational energy needs, as discussed previously.

For maintenance, the emissions varied significantly with design: the pine saw logs house design had significantly lower GHG impact. The difference from best to worst was very large, around 87%. This is mainly attributed to a GHG credit when pine saw logs are disposed after major renovations. Designs that contain more timber have a credit at the disposal phase as timber in landfill is modelled as a carbon sequester. The disposal phase also had a large difference from best to worst (95%), for the same reason.

CED: Across the whole life cycle, CED did not vary significantly with wall assemblage design: it varied only by 5% from best to worst house design. The small variation was due to the contribution of the construction phase, where brick had 12% higher CED than the pine saw log design. The operation, maintenance and disposal phases were very similar for all designs. The difference from best to worst was less than 10%.

Water use: On average, 98% of water use occurred during the construction and maintenance phases, similar to results for 3.6 and 3.7 star designs. Overall, the water use was similar for all designs.

Solid waste: On average, 88% of the waste impact occurred during the disposal phase, as expected. Overall, the level of emission varied significantly (by 22%) from best (weatherboard) to worst (brick), similar to the 3.7 star designs. The results for construction, operation and maintenance stages were similar for all designs; these life phases do not contribute significantly to waste, as for the 3.6 and 3.7 star designs. At disposal, the designs with timber exterior claddings (that is pine saw logs and weatherboard), have lower solid waste than other claddings.

In summary, for the 3.8 star rating designs, GHG, CED in construction, and solid waste varied significantly with design. Water usage was not affected significantly. The pine saw log house design had the lowest impact on several indicators. The results are similar to those for the 3.7 star rating house designs.

5.2.3.3 LCC results

The life cycle costs of the 3.8 star rating house designs with various wall assemblages are shown in Table 5.11. On average, 89% of the cost occurred during the construction and maintenance phases. Operations and disposal contributed a relatively low fraction of costs. The trends in results are similar to those for the 3.6 and 3.7 star rating house designs.

Table 5.11: Life cycle cost ($) of the 3.8 star rating house designs - wall assemblages

House Name	Construction	Operation	Maintenance	Disposal	Total
Brick House	136,800	19,100	54,500	5,700	216,100
Concrete House	138,100	19,000	54,400	5,900	217,400
FC sheet House	133,000	18,700	54,000	5,800	211,500
Pine logs House	153,100	19,000	65,800	5,600	243,500
Weatherboard House	134,300	19,000	55,000	5,800	214,100
Average %	**63.0**	**8.60**	**25.7**	**2.61**	**100**

Table 5.12 shows the % difference in life cycle costs for the 3.8 star rating house designs with various wall assemblages. The table shows that most of the house designs cost a similar amount (within 4% of the base house) except for the pine saw log design, which has a significantly higher cost (by 17%). Operation and disposal costs are similar for all the designs. These results are similar to those found for the 3.7 star rating house designs.

Table 5.12: Difference (%) in life cycle cost of the 3.8 star rating house designs -wall assemblages

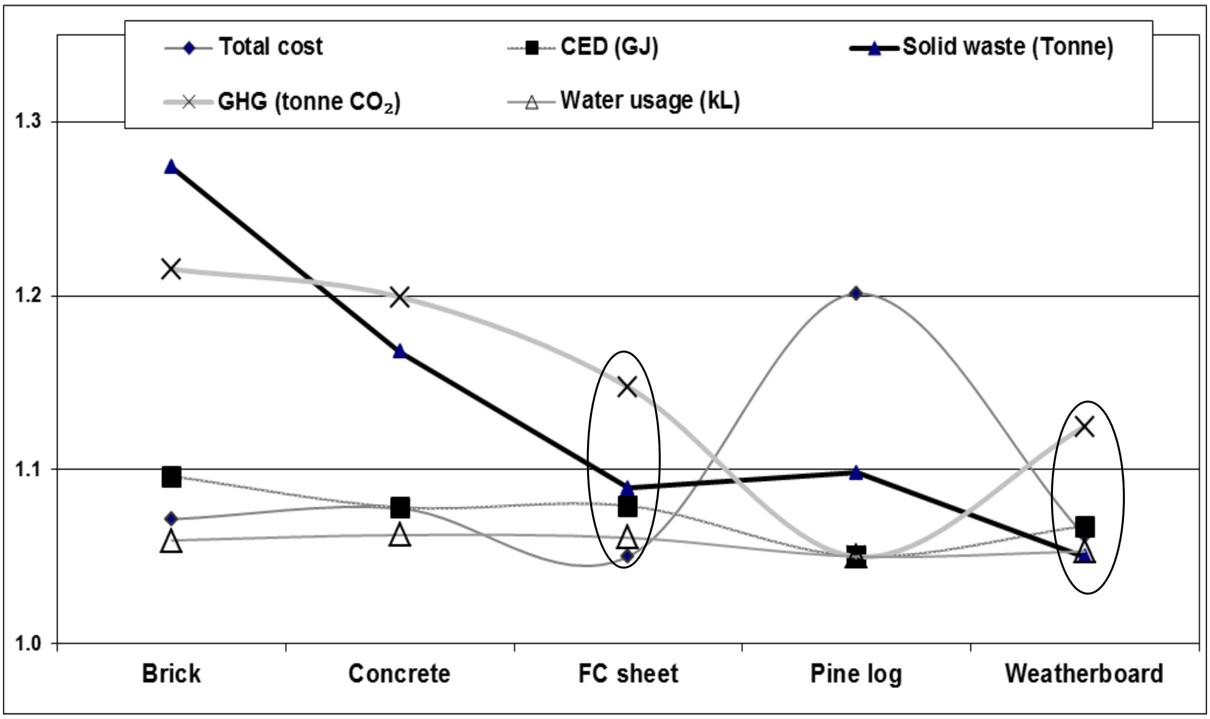
House Name	Construction	Operation	Maintenance	Disposal	Total
Base Case	0%	0%	0%	0%	0%
Brick House	6%	-6%	1%	1%	4%
Concrete House	7%	-7%	1%	5%	4%
FC sheet House	3%	-8%	0%	4%	1%
Pine log House	19%	-6%	22%	0%	17%
Weatherboard House	4%	-7%	2%	3%	3%

In summary, the construction and maintenance phases dominate LCC. Total operation and disposal costs are similar for all designs, except for higher construction and maintenance costs for the pine saw log designs. Overall, the results are similar to those for the 3.7 star house designs.

5.2.3.4 Discussion

Figure 5.5 shows a multi-objective approach for the 3.8 star house designs with various wall assemblages, showing normalised values for LCC and selected environmental impact indicators. The figure shows that the weatherboard and the FC sheet house are the best designs, as for the 3.7 star designs.

Figure 5.5: Normalised LCC and selected LCA impacts for the 3.8 star rating house designs -wall assemblages



House designs with 3.9 star rating are considered in the next section.

5.2.4 Results for the 3.9 star rating house designs - wall assemblages

5.2.4.1 Operational energy results

Results for the 3.9 star rating houses with various wall assemblages are presented in this section. The same cladding types are used, as for the 3.7 and 3.8 star rating house designs. These are brick, concrete, FC sheet, pine saw log and weatherboard.

Table 5.13: Rated energy requirements of the 3.9 star rating house designs - wall assemblages

Annual Energy Requirements (MJ/m^2.annum)	Brick	Concrete	FC sheet	Pine Log	Weatherboard
Heating	14.4	14.4	14.5	14.6	13.7
Cooling-sensible	42.8	43	41.6	42.7	42.8
Cooling-latent	17.0	16.8	16.9	17.1	17.4
Total (Energy)	74.2	74.2	73.0	74.4	73.9

The annual energy requirements for 3.9 star designs modelled in *AccuRate* are shown in Table 5.13. Full details of the assemblage designs were given in Section 4.3.2. The results show that the total operational energy requirements were similar for all house designs, as for the houses with 3.6, 3.7 and 3.8 star rating designs. As discussed in Chapter 4, the designs were constrained to achieve the same star rating. The LCA results are discussed in the next section.

5.2.4.2 LCA results

A summary of results for selected life cycle impact indicators of the houses with 3.9 star wall designs are given in Table 5.14.

Table 5.14: LCA results for the 3.9 star rating house designs - wall assemblages

GHG (Tonne)					
House Name	Construction	Operation	Maintenance	Disposal	Total
Brick House	29.5	44.3	5.95	-4.64	75.2
Concrete House	28.8	44.3	5.97	-4.12	75.0
FC Sheet House	26.7	43.5	6.43	-5.15	71.5
Pine Saw log House	25.1	44.4	3.43	-7.99	65.0
Weatherboard House	25.7	44.3	5.00	-5.25	69.8
Average, (STDEV)	27.2, (1.90)	44.2, (1.20)	5.36, (0.37)	-5.43, (1.50)	71.3, (4.20)
Percentage (%)	**38.1**	**61.9**	**7.52**	**-7.62**	**100**
Cumulative Energy Demand (GJ)					
House Name	Construction	Operation	Maintenance	Disposal	Total
Brick House	426	511	119	14.8	1070
Concrete House	399	511	120	13.8	1040
FC Sheet House	411	502	127	13.8	1050
Pine Saw log House	369	512	117	14.2	1010
Weatherboard House	401	509	118	13.8	1040
Average, (STDEV)	401, (20.7)	509, (3.88)	120, (3.74)	14.1, (0.43)	1040, (21.0)
Percentage (%)	**38.4**	**48.7**	**11.5**	**1.35**	**100**
Water Use (kL)					
House Name	Construction	Operation	Maintenance	Disposal	Total
Brick House	1950	61.7	1080	-0.72	3100
Concrete House	1960	61.7	1080	-0.66	3110
FC Sheet House	1950	60.4	1090	-0.42	3100
Pine Saw log House	1930	61.7	1080	-1.27	3070
Weatherboard House	1940	62.2	1080	-0.43	3080
Average, (STDEV)	1950, (13.1)	61.6, (0.67)	1080, (5.96)	-0.70, (0.35)	3090, (16.8)
Percentage (%)	**62.9**	**1.99**	**35.0**	**-0.02**	**100**
Solid Waste (Tonne)					
House Name	Construction	Operation	Maintenance	Disposal	Total
Brick House	4.07	1.54	5.53	85.7	96.8
Concrete House	4.06	1.54	5.53	76.9	88.1
FC Sheet House	3.87	1.51	4.95	71.3	81.6
Pine Saw log House	3.85	1.54	4.96	72.2	82.6
Weatherboard House	3.86	1.55	3.63	69.6	78.7
Average, (STDEV)	3.94, (0.11)	1.54, (0.02)	4.92, (0.78)	75.1, (6.48)	85.5, (7.15)
Percentage (%)	**4.61**	**1.80**	**5.75**	**87.8**	**100**

In broad terms, the results show that different impact categories are dominated by different life stages, similar to the results for 3.6, 3.7 and 3.8 star rating house designs. The categories of GHG and CED are dominated by construction and operation, water usage is dominated by construction and maintenance, and solid waste is dominated by the disposal phase.

GHG: For the category of GHG, the emissions varied across the whole life cycle, by 16% from best (pine saw log) to worst design (brick and concrete). The differences in emissions are mainly during the construction phase, where the brick house emissions were 17% higher than the pine saw log house. This reflects that brick manufacturing requires energy intensive process, similar to results for the 3.7 and 3.8 star designs. The operation phase was similar for all designs. This was expected, as all the designs have the same star rating. For maintenance, the GHG emissions varied significantly with design. The difference from best (pine saw log) to worst (brick) was very large (around 74%) similar to the 3.7 and 3.8 star designs. Designs that contain more timber have a credit at disposal phase as timber in landfill is modelled as a carbon sequester. For disposal, the difference from best to worst was also very large, about 94%, similar to the results for the 3.7 and 3.8 star rating house designs.

CED: Across the whole life cycle, CED did not vary significantly: it varied only by 6% from best to worst house design, similar for 3.7 and 3.8 star designs. Only in the construction phase, CED was significantly affected by designs: the best design (pine saw log) had 15% lower CED than the worst (brick). The operations, maintenance and disposal phases were similar for all designs, as for the 3.7 and 3.8 star designs.

Water use: For the category of water use, on average, construction and maintenance contributed to the highest water use, similar to the results for the other star rating house designs. Overall, all designs had similar impacts for water use, as for the other star rating house designs.

Solid waste: For the category of waste impact, on average, the life stage of disposal contributed the most impact (88%), as expected. It varied significantly (by 23%) from best (weatherboard) to worst (brick) house design. The results for construction, operation and maintenance stages were similar for all designs; these life phases do not contribute significantly to waste, similar to the results for other star rating house designs. At disposal, the designs with timber exterior claddings (that is pine saw log and weatherboard), have lower solid waste than other designs, attributed to carbon sequestration of timber in landfill.

In summary, for the 3.9 star designs, GHG, CED in construction, and solid waste varied significantly with design. Water usage was not affected significantly. The pine saw log clad designs performed best in several categories. Overall, the results are similar to those for the other star rating house designs.

5.2.4.3 LCC results

Table 5.15 shows the life cycle cost for the 3.9 star rating house designs with various wall assemblages. The total costs are quite similar ($215,000) for all house designs, except for the pine saw log house, which is significantly higher. On average, construction and maintenance contributed most to the total life cycle cost, followed by operation.

Table 5.15: Life cycle cost ($) for the 3.9 star rating house designs -wall assemblages

House Name	Construction	Operation	Maintenance	Disposal	Total
Brick House	140,000	18,000	55,000	5,900	219,000
Concrete House	139,000	18,000	54,000	5,900	217,000
FC sheet House	134,000	18,000	54,000	5,800	212,000
Pine logs House	155,000	19,000	66,000	5,600	245,000
Weatherboard House	135,000	18,000	55,000	5,800	214,000
Average %, (ST.DEV)	63.4, (8580)	8.31, (138)	25.6, (5080)	2.61, (109)	100, (13500)

Table 5.16: Difference (%) in life cycle cost of the 3.9 star rating houses designs -wall assemblages

House Name	Construction	Operation	Maintenance	Disposal	Total
Base Case	0%	0%	0%	0%	0%
Brick House	9%	-9%	1%	4%	5%
Concrete House	8%	-9%	1%	5%	5%
FC sheet House	4%	-10%	0%	4%	1%
Pine logs House	21%	-9%	22%	0%	18%
Weatherboard House	5%	-9%	2%	3%	3%

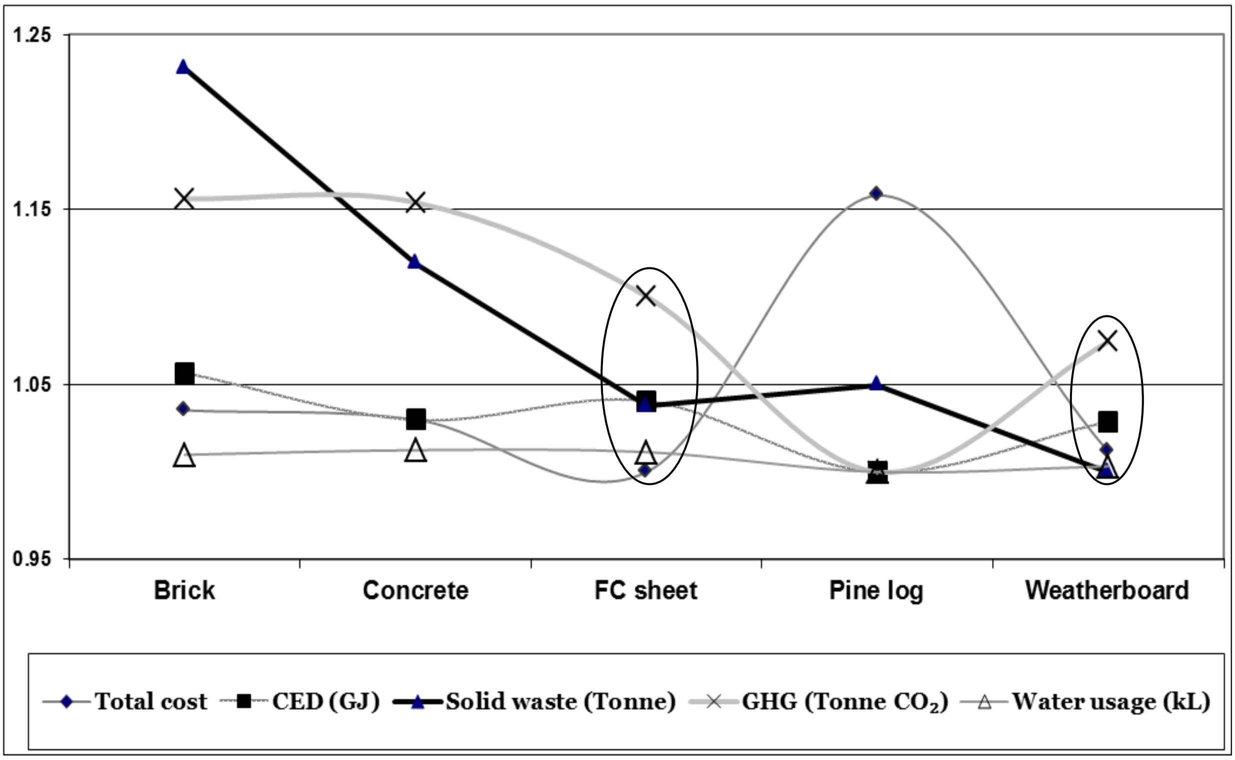
Table 5.16 shows the percent difference in life cycle costs for the five 3.9 star house designs compared to the base case. The table shows that most of the house designs cost a similar amount (within 5% of the base house) except for the pine saw log house design, which has a significantly higher cost (by 18%). Operation and disposal costs are similar for all the 3.9 star rating house designs.

In summary, the construction and maintenance phases dominate LCC. All the costs are similar for all designs, except for higher construction and maintenance costs for the pine saw log house. Overall, the results are similar to other star rating house designs.

5.2.4.4 *Discussion*

Figure 5.6 shows normalised LCC and selected environmental impact categories. The weatherboard houses and FC sheet are the best designs, as for the 3.7 and 3.8 star designs.

Figure 5.6 Normalised LCC and LCA of the houses with 3.9 star rating -wall design



In summary, FC sheet and weatherboard are identified as “good” designs when multi-objective functions are used, as for 3.6 to 3.8 star rating designs.

A comparison of all the house designs is discussed in the next section, to assess whether the optimum design depends on the star rating.

5.3 COMPARISON OF RESULTS FOR HOUSE DESIGNS WITH STAR RATINGS

The results for the house designs with 3.6 to 3.9 star ratings are compared in this section to assess the effects of star rating on the optimum design. For simplicity, the assemblage designs are denoted as case study house (base case), brick house (BH), concrete house (CH), FC sheet house (FC), pine saw log house (PL) and weatherboard house (WB). The detailed results for the house with 3.6 to 3.9 star wall designs are presented first. Then, the optimum designs are identified using a graphical approach.

5.3.1 Comparison of LCA results

GHG: The life cycle GHG results for all house designs are given in Table 5.17. On average, construction contributed 37%, operation 63%, maintenance 7% and disposal -7% to the total emissions. The standard deviation (St. Dev.) is small for all life stages. However, the total emissions varied significantly (by 20%) from best (PL 3.9) to worst (BH3.7) house design.

Table 5.17: GHG emissions for 3.6 to 3.9 star rating house designs -wall assemblages

	GHG (Tonne)				
House Name	**Construction**	**Operation**	**Maintenance**	**Disposal**	**Total**
BH 3.9	29.5	44.3	5.96	-4.64	75.2
BH 3.8	29.2	45.7	5.96	-4.09	76.8
BH 3.7	29.0	46.9	5.96	-4.09	77.8
CH 3.9	28.8	44.3	5.97	-4.12	75.0
CH 3.8	28.6	45.2	5.97	-4.12	75.7
CH 3.7	28.5	46.6	5.97	-4.12	76.9
CH 3.6	28.5	47.3	5.97	-4.12	77.6
FC 3.9	26.7	43.5	6.43	-5.15	71.5
FC 3.8	26.5	44.7	6.43	-5.25	72.3
FC 3.7	26.2	46.1	6.43	-4.21	74.5
FC 3.6	26.1	47.2	6.43	-4.21	75.5
PL 3.9	25.1	44.4	3.43	-7.99	65.0
PL 3.8	24.9	45.5	3.43	-7.99	65.9
PL 3.7	24.8	46.5	3.43	-7.99	66.7
WB 3.9	25.7	44.3	5.00	-5.25	69.8
WB 3.8	25.5	45.5	5.00	-5.25	70.8
WB 3.7	25.3	47.1	5.00	-4.70	72.6
WB 3.6	25.1	48.3	5.00	-4.70	73.7
Base Case	26.0	48.0	6.43	-4.21	76.2
Average (St. Dev.)	26.9 (1.68)	45.9 (1.38)	5.49 (1.05)	-5.06 (1.37)	73.1 (3.95)
Average %	36.7	62.7	7.50	-6.92	100

The results show that the house designs with higher star ratings had lower overall GHG emissions: for example, BH3.9 has lower total emissions than BH3.8 and BH3.7. The designs with higher star ratings had higher GHG in the construction and disposal phases, but this was offset by lower emissions during the operation phase. The GHG emissions decreased on average by around 14% per star rating increase. This result is comparable to other Australian studies, where GHG emissions decreased as star rating increased. The rate of decrease of emissions ranged from 20-30% (DSE 2007) to 9-17% per star rating (Carre 2011).

CED: The CED impacts for all the houses design are given in Table 5.18. On average, construction contributed 37%, operation 50%, maintenance 11% and disposal 1% to the total CED. The standard deviation is high for construction and operation life stages as well as for the total CED. The emissions varied significantly from best to worst design in construction (by 16%), operation (11%), maintenance (by 8%) and disposal (by 14%). However the best in one life stage was not the best in the others, so overall the total emissions did not vary significantly (only 6%) from best (PL 3.9) to worst (CH3.6) house design.

Table 5.18: CED for 3.6 to 3.9 star rating house designs - wall assemblages

	CED (GJ)				
House Name	**Construction**	**Operation**	**Maintenance**	**Disposal**	**Total**
BH 3.9	426	511	119	14.8	1070
BH 3.8	410	528	119	14.3	1070
BH 3.7	408	545	119	14.3	1090
CH 3.9	399	511	120	13.8	1040
CH 3.8	397	523	120	13.8	1050
CH 3.7	395	541	120	13.8	1070
CH 3.6	395	551	120	13.8	1080
FC 3.9	411	502	127	13.8	1050
FC 3.8	397	517	127	13.3	1050
FC 3.7	381	534	127	13.0	1050
FC 3.6	380	549	127	13.0	1070
PL 3.9	369	512	117	14.2	1010
PL 3.8	367	526	117	14.2	1020
PL 3.7	366	540	117	14.2	1040
WB 3.9	401	509	118	13.8	1040
WB 3.8	388	522	118	13.8	1040
WB 3.7	373	542	118	13.3	1050
WB 3.6	370	558	118	13.3	1060
Base Case	378	560	127	13.0	1080
Average (St. Dev.)	390 (17)	530 (18)	121 (4)	13.8 (0.5)	1,050 (20)
Average %	37.0	50.3	11.4	1.3	100

The results show that the designs with higher star ratings had lower overall CED, similar to GHG. The designs with higher star ratings had significantly increased CED in construction and disposal phase due to the greater amount of material used, but it was counterbalanced by lower operational energy. The CED impacts decrease by around 10% per star rating as the star rating increases. There are not many similar studies reported in the literature. However, this finding is comparable to another Australian study that reported CED decreased as star rating increased. The rate of decrease was 18% per star rating for a heritage listed building (Iyer-Raniga & Wong 2012). The difference in the rate of decrease may be attributed to differences in building type and model assumptions.

Water use: The water usages for all the house designs are given in Table 5.19.

Table 5.19: Water use (kL) of the houses with 3.6 to 3.9 star rating -wall design

House Name	Construction	Operation	Maintenance	Disposal	Total
BH 3.9	1950	61.7	1080	-0.72	3100
BH 3.8	1950	63.2	1080	-0.64	3100
BH 3.7	1950	64.1	1080	-0.64	3100
CH 3.9	1960	61.7	1080	-0.66	3110
CH 3.8	1960	62.6	1080	-0.66	3110
CH 3.7	1960	63.7	1080	-0.66	3110
CH 3.6	1960	64.3	1080	-0.66	3100
FC 3.9	1950	60.4	1090	-0.42	3100
FC 3.8	1950	61.6	1090	-0.56	3100
FC 3.7	1950	63.5	1090	-0.29	3100
FC 3.6	1950	64.3	1090	-0.29	3100
PL 3.9	1930	61.7	1080	-1.27	3070
PL 3.8	1930	63.0	1080	-1.27	3070
PL 3.7	1930	63.5	1080	-0.36	3070
WB 3.9	1940	62.2	1080	-0.43	3080
WB 3.8	1930	64.0	1080	-0.43	3080
WB 3.7	1930	65.6	1080	-0.36	3080
WB 3.6	1930	66.8	1080	-0.36	3080
Base Case	1940	65.4	1090	-0.29	3100
Average (St. Dev.)	1,940 (11.9)	63.3 (1.6)	1,080 (5.9)	-0.58 (0.3)	3,090 (15)
Average %	**62.8**	**2.2**	**35.0**	**0.0**	**100**

On average, construction contributed 63%, operation 2%, maintenance 35% and disposal 0% to the total water use. The difference from highest to lowest in the construction phase is 30kL, which is a significant difference (at the 95% confidence level). The difference from highest to lowest in the total water usage is 40 kL, also a significant different (at the 95% confidence level). Both are due to variation with design, with weatherboard (WB) using the least water and Autoclave Aerated Concrete blocks (CH) the most. . Water use did not vary significantly with star rating: it varied less than 0.5% from highest to lowest star rating for any one type of house design. There are small but not significant differences in water usage during the operation life phase. This is due to differences in energy usage, as the life cycle inventory for energy production includes water usage. Very few studies reported water usages that are comparable: Iyer-Raniga & Wong (2012) reported that star rating had no significant effect on water usage for their two designs.

Waste impact: The waste impact of all the houses of 3.6 to 3.9 star wall designs are given in Table 5.20.

Table 5.20: Solid Waste for 3.6 to 3.9 star rating house designs - wall assemblages

	Solid Waste (tonne)				
House Name	**Construction**	**Operation**	**Maintenance**	**Disposal**	**Total**
BH 3.9	4.07	1.54	5.53	85.7	96.8
BH 3.8	4.07	1.58	5.53	85.1	96.3
BH 3.7	4.06	1.60	5.53	85.1	96.3
CH 3.9	4.06	1.54	5.53	76.9	88.1
CH 3.8	4.05	1.56	5.53	76.8	88.0
CH 3.7	4.05	1.59	5.53	76.8	87.9
CH 3.6	4.05	1.61	5.53	76.8	87.9
FC 3.9	3.87	1.51	4.95	71.3	81.6
FC 3.8	3.87	1.54	4.95	71.4	81.8
FC 3.7	3.87	1.59	4.95	70.4	80.8
FC 3.6	3.86	1.61	4.95	70.4	80.8
PL 3.9	3.85	1.54	4.96	72.2	82.6
PL 3.8	3.85	1.57	4.96	72.1	82.5
PL 3.7	3.84	1.59	4.96	72.0	82.4
WB 3.9	3.86	1.55	3.63	69.6	78.7
WB 3.8	3.86	1.60	3.63	69.6	78.7
WB 3.7	3.86	1.64	3.63	69.1	78.2
WB 3.6	3.85	1.67	3.63	69.0	78.2
Base Case	3.86	1.63	4.95	70.3	80.8
Average (St. Dev.)	3.93 (0.1)	1.58 (0.4)	4.89 (0.7)	74.3 (5.6)	85.0 (6.2)
Average (%)	**4.7**	**1.87**	**5.8**	**87.7**	**100**

On average, construction contributed 5%, operation 2%, maintenance 5% and disposal 88% to the total solid waste. The standard deviation is low for all life stages as well as for the total solid waste. Solid waste showed no significant correlation with star rating. However, it varied significantly with design: it varied by 24% from best (WB3.6) to worst (BH3.9) design. There are small but not significant differences in solid waste during the operation life phase. This is due to differences in energy usage, as the life cycle inventory for energy production includes solid waste. There are a few studies and none of these considered the effect of different star ratings on solid waste (Carre 2011; Kahhat et al 2009; Lippike et al 2004).

In summary, changing the star rating on wall assemblage design had a significant effect on GHG (by 20% from best to worst) and solid waste (by 24% from best to worst), but not on CED or water usage. Changing the star rating had a significant effect on different environmental impact categories, namely, GHG (total) and CED (construction, operation and disposal) but not on water usage. Overall, the GHG emissions decreased by around 14% per star rating and CED impacts by around 10% per star rating increase. These were attributed to offset of the higher use of resources (i.e. insulation) by savings in operations at higher star ratings.

5.3.1 Comparison of LCC results

The LCC of 3.6 to 3.9 star rating house designs with various wall assemblages are given in Table 5.21.

Table 5.21: LCC of 3.6 to 3.9 star rating houses designs - wall assemblages

	LCC ($)				
House Name	**Construction**	**Operation**	**Maintenance**	**Disposal**	**Total**
BH 3.9	140,000	18,500	54,500	5,900	219,000
BH 3.8	137,000	19,100	54,500	5,700	216,000
BH 3.7	136,000	19,800	54,500	5,700	216,000
CH 3.9	139,000	18,500	54,400	5,900	218,000
CH 3.8	138,000	19,000	54,400	5,900	217,000
CH 3.7	137,000	19,700	54,400	5,900	217,000
CH 3.6	137,000	20,000	54,400	5,900	217,000
FC 3.9	134,000	18,200	53,900	5,800	212,000
FC 3.8	133,000	18,700	54,000	5,800	211,000
FC 3.7	130,000	19,300	54,000	5,600	209,000
FC 3.6	129,000	20,300	53,900	5,600	209,000
PL 3.9	155,000	18,600	65,800	5,600	245,000
PL 3.8	153,000	19,000	65,800	5,600	243,000
PL 3.7	152,000	19,600	65,800	5,600	243,000
WB 3.9	135,000	18,400	55,000	5,800	214,000
WB 3.8	134,000	19,000	55,000	5,800	214,000
WB 3.7	131,000	19,600	55,000	5,600	211,000
WB 3.6	130,000	20,200	55,000	5,600	211,000
Base Case	129,000	20,300	54,000	5,600	209,000
Average (St. Dev.)	137,000 (8000)	19,300 (700)	56,200 (4300)	5,700 (100)	218,000 (12000)
Average %	**62.8**	**8.8**	**25.7**	**2.7**	**100**

On average, construction contributed 63%, operation 9%, maintenance 26% and disposal 3% to the total LCC. The standard deviation is low for all life stages as well as for the total LCC. However, LCC showed a significant increase with star rating, of around $30000 for total cost (14%), and $29000 for construction costs (21%) per star rating. It also varied significantly with design: it varied by 17% from highest (PL3.9) to lowest (Base case/FC3.6/FC3.7) design. If the expensive pine log house designs are removed, it varies by only 5% from the highest (BH3.9) to lowest design, the increase with star rating drops to around $14000 for total cost (6.5%) and $19000 per star rating for construction costs (14%).

Two recent Australian studies also found that initial costs increased as star rating increased. McLeod & Fay (2011) and Belusko & O'Leary (2010) reported that an increase of 1-2% in initial costs was required to increase a house star rating from 4 to 5 star. The bigger increase in construction cost reported in this study may be attributed to evaluation of a wider range of house designs in this study. Unfortunately, they did not report other operation costs, so it is not possible to determine to what degree savings might offset their higher costs of construction in the operation phase.

In summary for both LCA and LCC, wall assemblage design had a significant effect on GHG (by 20% from best to worst), solid waste (by 24% from best to worst) and LCC (by 17% from highest to lowest), but not on CED or water usage. The house designs with higher star ratings had significantly lower GHG (total) and CED (construction, operation and disposal). Overall, the GHG emissions decreased by around 14% and CED decreased by around 10% per star rating as star rating increased. For water use and solid waste, there was no significant effect of star rating. The effect of star rating on LCC depended on the range of house designs considered: it varied by 7 to 14% for total LCC, and by 14 to 21% for construction costs depending on whether pine log houses were considered. The higher costs of construction were partially offset by savings in the operation phase: total LCC also increased.

In the following section, the house designs with various star ratings and wall assemblages are analysed using a graphical approach to identify the best designs.

5.4 GRAPHICAL ANALYSIS OF ALL THE HOUSE DESIGNS: VARIOUS WALL ASSEMBLAGES

Where multiple designs are available, it is a critical question to determine which, if any, are the optimal designs. The stakeholders may be interested in one or more variables (i.e. environmental or economic). In the following discussion, first a single then a multi-objective function approach is used to identify the "best" or best set of optimum designs for all the house designs with 3.6 to 3.9 star rating and various wall assemblages.

5.4.1 Single-objective approach: wall assemblages

In this single-objective approach, one objective function variable is minimised at a time to identify the optimum design. Selected life cycle environmental impacts (GHG and CED) and LCC for all the 19 house designs with various wall assemblages are shown in Figure 5.7. The results show that the "best" design and ranking of wall assemblages is different for each impact category.

Figure 5.7: GHG, Cumulative Energy Demand and LCC for the base case and modified houses with wall-designs

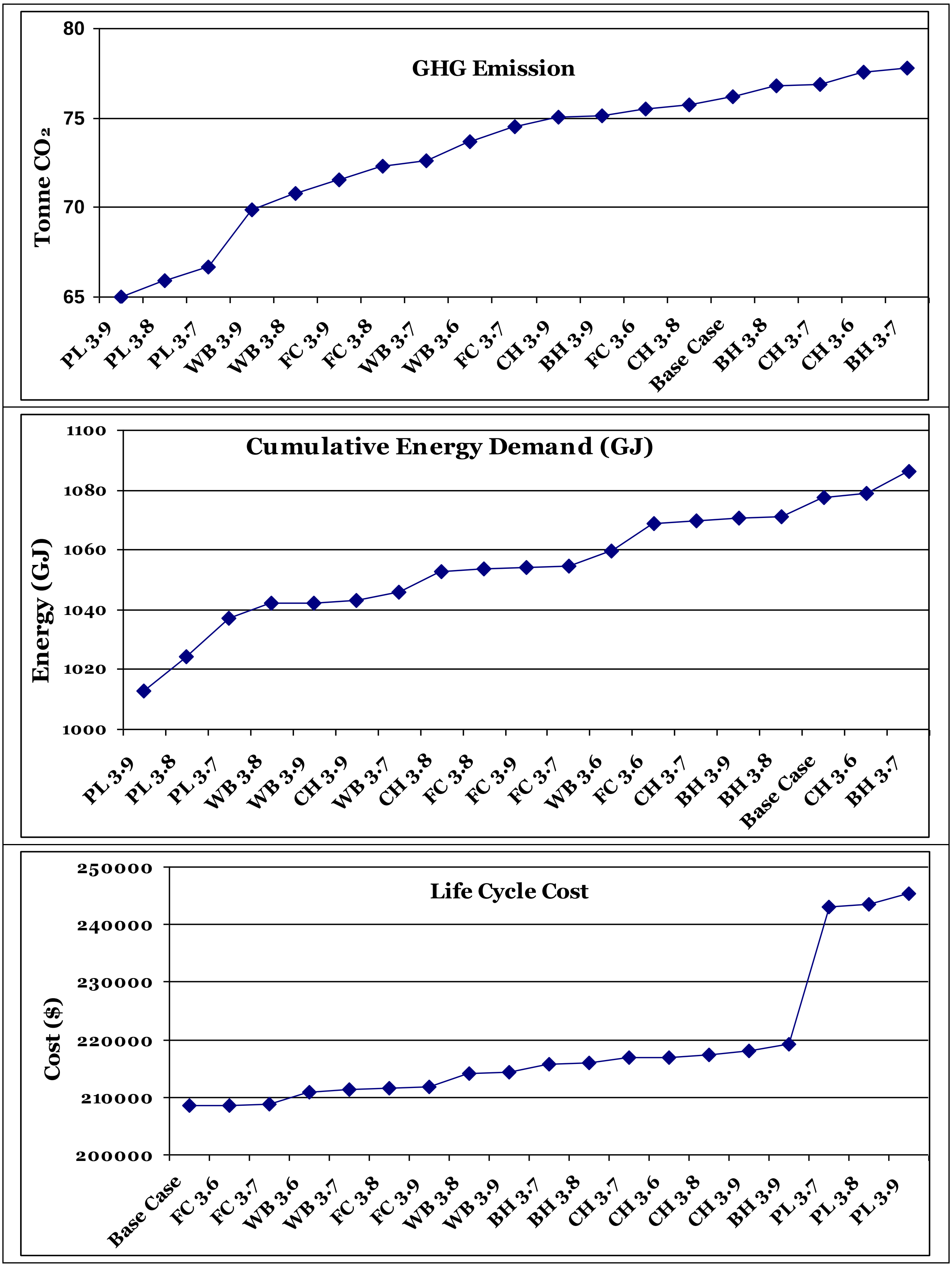


Figure 5.7 shows that for GHG and CED, SOO identifies the best design as the pine saw logs and the worst is brick. For LCC, base case and FC sheet have the same

optimum (minimum) cost, while pine saw logs have the highest costs. Although the difference from one particular design to the next is minimal, the difference between best to worst design is significant, as discussed in section 5.3.1 (LCA) and 5.3.2 (LCC). Hence, taking a single objective approach is ineffective in identifying the best design, as the optimum depends on which variable is considered.

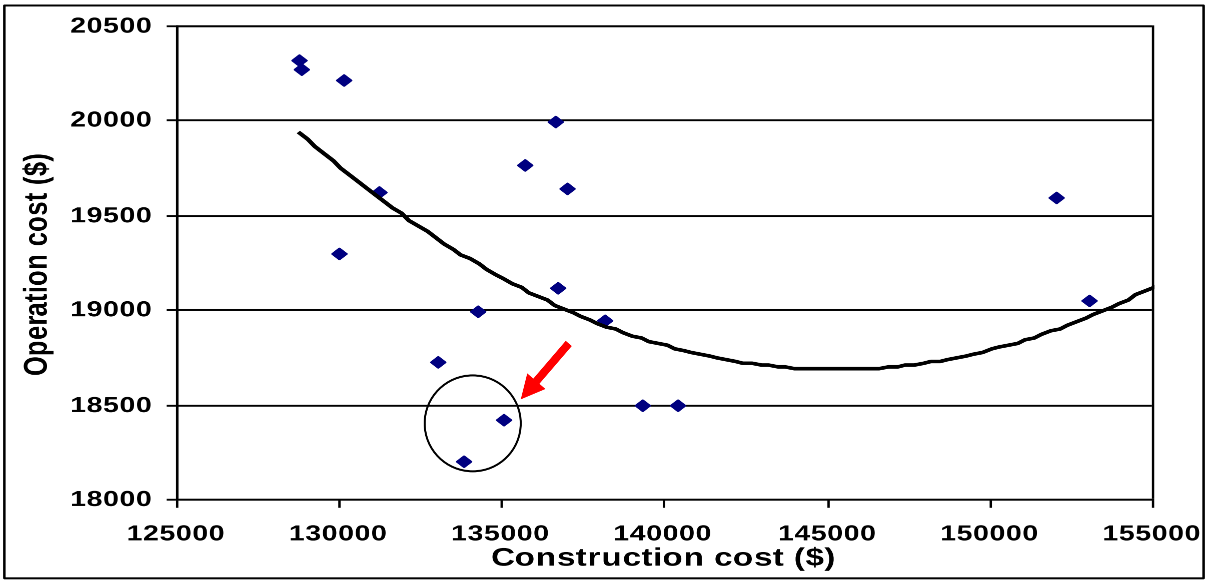
5.4.2 Multi-objective approach: wall assemblages

If a multi-objective approach is taken, two or multiple variables at a time can be minimised. In this section, multi-objective is used to identify the optimum design or set of designs, with two and multiple objective functions.

5.4.2.1 Multi-objective approach (2 variables)

Figure 5.8 shows a multi-objective approach for two variables, operation and construction costs. It shows there are two good designs (ringed). These are FC3.6 and FC3.7. These have both low construction and operation costs. These do not have the lowest construction costs, but they have the best trade-off. They are the points furthest away from the best-fit line to all the house design data.

Figure 5.8: Operation and construction costs of the houses with 3.6 to 3.9 star rating - wall design

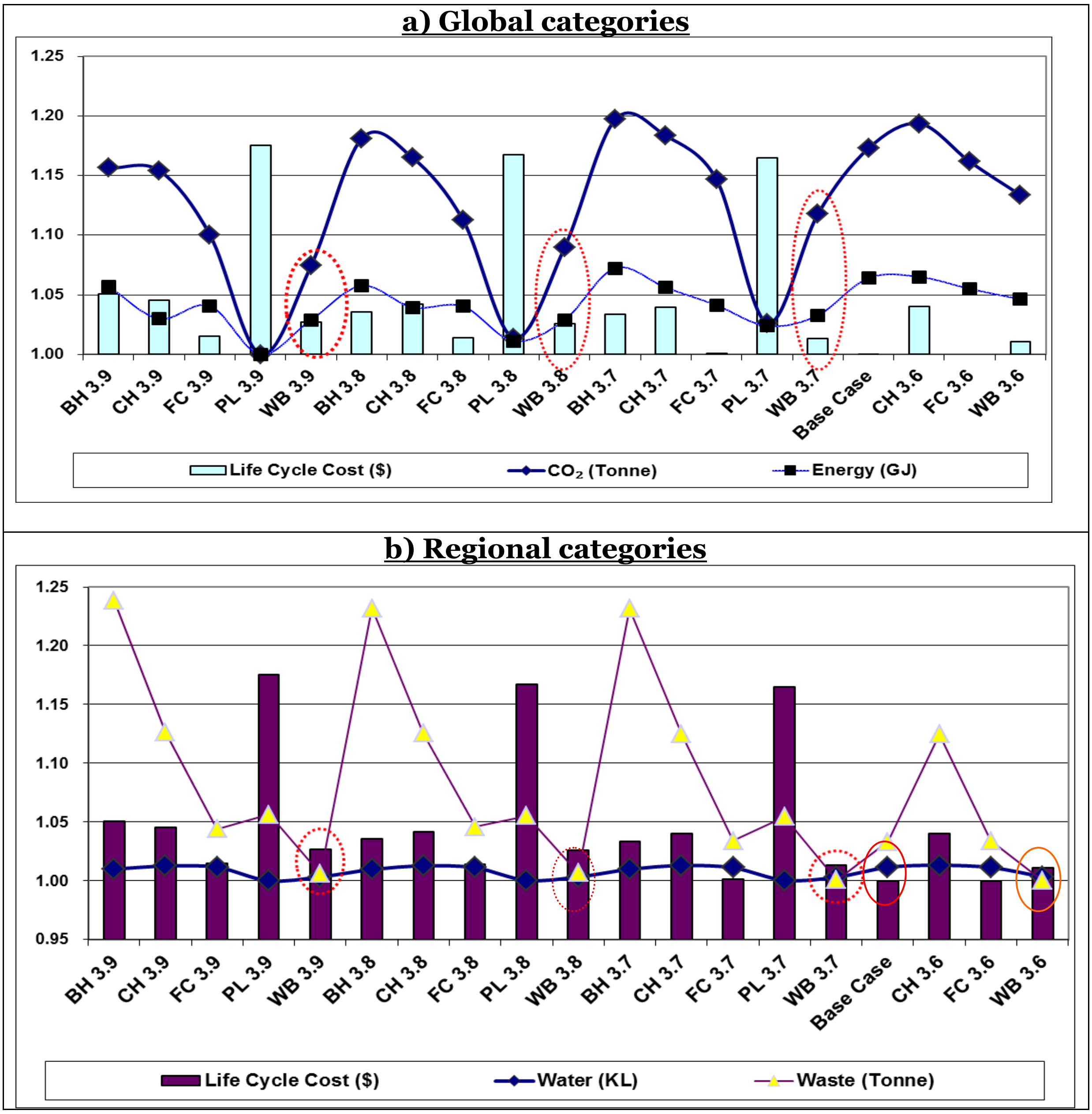


If a different pair of indicators was chosen the outcome might be the same or different. Hence, this approach is also ineffective in identifying the best design, as the optimum depends on which objective functions are considered.

5.4.2.2 *Multi-objective approach (multiple variables)*

In multi-objective approach, multiple variables at a time are considered. The results for all 19 houses with 3.6 to 3.9 star rating wall assemblages shown in Figure 5.9 for global categories (i.e. CED and GHG) with life cycle costs, and regional categories (i.e. water use and waste impact) with life cycle cost. Normalised data are shown.

Figure 5.9 Normalised LCC and LCA results for a) global and b) regional categories



The best designs have values close to unity with minimal spread: that is, all variables are minimised. Figure 5.9 shows that there are several good designs (ringed). These give a better performance across a range of categories. For global categories, the best designs are weatherboard houses WB3.9 and WB3.8. For regional categories, the best design is weatherboard houses WB3.6. Some of the FC sheet houses and the base case are also good designs. The figure shows that it is difficult to identify the best design from one graph when just 3 to 5 objective functions are considered for a large number of designs. For a large number of objective functions or designs, the graphical approach is not suitable. An alternative approach is needed, such as using a Mathematical Programming model. Whether such a method can identify the best designs will be discussed in Chapter 8.

The summary of results for the best designs is given in the next section.

5.4.3 Comparison of optimisation results: wall assemblages

Table 5.22 summarises the results for “best” designs from the different approaches used in the previous sections.

Table 5.22: Comparison of results from different optimisation approaches

Approach	Objective functions	Star rating	Best wall assemblage
Single-objective	GHG, CED	Higher	Pine saw log
Single-objective	LCC	Lower	Weatherboard/ FC sheet
Multi-objective (two variables)	Operation and construction cost	Lower	FC sheet
Multi-objective (Three variables-global categories)	GHG, CED and LCC	Higher	Weatherboard
Multi-objective (Three variables-regional categories)	Water, waste and LCC	Lower	Weatherboard/ FC sheet
Multi-objective (all five variables)	GHG, CED, water, waste and LCC	Higher	Weatherboard

It shows that the "best" design depends on which approach is taken and which impact categories are selected for the objective functions. A single or set of best designs may be identified.

5.5 SUMMARY

In summary, changing the wall assemblage and star rating has a significant effect on LCA and LCC results. In particular, GHG, solid waste and LCC are significantly affected by assemblage design, while GHG, CED and LCC are affected by star rating. Water use was not sensitive to wall assemblage design nor star rating.

To identify the optimum design, there is a significant difference in the outcomes depending on whether a single or multi-objective evaluation is taken. If a single-objective is taken, the optimum depends on which objective functions are considered. If a multi-objective approach is taken, there are many "best" designs. A graphical approach is limited in its capacity to identify optimum designs: the more designs and the more objectives, the more difficult it is to identify the best design. To find the optimum design with more confidence, an optimisation algorithm must be used. This approach will be presented in Chapter 8.

Evaluation of the effect on optimum house design of different roof and floor assemblages is also needed to get a full picture of the environmental and economic costs of whole buildings, considering both LCA and LCC. The results of roof and floor assemblage designs are presented in Chapters 6 and 7.

CHAPTER 6: ROOF ASSEMBLAGE DESIGN

Introduction; Effect of roof assemblage design on LCA and LCC; Graphical analysis of all the house designs: roof assemblages; Summary

6.1 INTRODUCTION

In this chapter, the results for the LCA and LCC of all roof assemblage designs are presented. The results were derived using the model and assumptions described in Chapters 3 and 4. The effects of modified roof designs were evaluated. The case study house was used as the base case for modified roof assemblage designs. Only roof assemblages were varied while floor and wall assemblages were kept same, similar to the approach undertaken in wall assemblage designs (in Chapter 5). The results are analysed for the whole building on a whole of life cycle basis. The results for modified floor assemblage designs are presented in Chapter 7.

The modified roof designs were varied in roofing types, rooftop materials, type and position of insulation and air gap thickness and position. Each design is varied to achieve a chosen star rating, for example, by adding slightly thicker insulation under the rooftop, and inside the ceiling. Three roof types and two rooftop materials are selected, typical of the Australian building industry. The chosen roofing types are gable, skillion flat and skillion pitch roof. The two chosen rooftop materials are metal and concrete tiles. Metal is chosen for skillion roof. Therefore, the four roof designs are gable metal, gable tile, skillion flat and skillion pitch roof. Flat ceilings were selected for all designs, typical of the Australian building industry. The economic and environmental impact of the modified roof assemblages on building whole life cycle is presented first. Then, the optimum roof designs are identified using a graphical approach.

6.2 EFFECT OF ROOF ASSEMBLAGE DESIGN ON LCA AND LCC

This section reports how different assemblages of roof designs affect the life cycle environmental impacts and costs over various life stages. Four roof assemblage designs are made, each with two different star ratings (3.6 and 3.9 stars). The different assemblage designs are compared, as well as the low and high star rating designs. This is an effective way to identify the effects of design on the life cycle impact of materials on buildings (Carre 2011; Lippike et al 2004; Morrissey & Horne 2011).

The two selected star ratings are chosen as follows: 3.6 stars is the rating for the case study house, and 3.9 stars is the maximum rating possible for several of the roof designs. Constraints on the roof design included minimum and maximum roof and ceiling thicknesses, to meet Australian Standard AS-1562 (Standards Australia 1992). Full details of the modified roof designs are given in Section 4.3.3.

6.2.1 Results for the 3.6 and 3.9 star rating house design-roof assemblages

The annual operational energy requirements for heating and cooling are estimated on MJ/m^2.annum basis. The energy requirements are then multiplied by the conditioned floor area and building life span to estimate the full life cycle energy usage. This is then used as input to the LCA, using the same approach described in Section 4.6.1. For each figure in this section, the assemblage designs are abbreviated as follows: base case (BC), gable metal roof (MR), gable tile roof (TF), skillion flat (SF), and skillion pitch (SP).

6.2.1.1 Operational energy results

The operational energy requirements of the house designs with various roof assemblages and 3.6 and 3.9 star ratings are shown in Table 6.1.

Table 6.1: Energy requirements for houses designs with various roof assemblages

Star Rating & House Name		**Heating Energy**	**Cooling Energy**		**Total Annual Energy (MJ/m^2.annum)**
			Cooling-Sensible	**Cooling-Latent**	
3.6 star	BC	18.2	46.0	17.3	81.5
	MR	17.6	45.0	17.3	79.9
	SF	17.7	45.7	17.6	81.0
	SP	17.0	45.8	17.8	80.6
	TF	17.6	45.0	17.3	79.9
Average		**17.6**	**45.5**	**17.5**	**80.6**
3.9 star	MR	14.8	40.3	16.4	71.5
	SF	16.1	40.2	17.5	73.8
	SP	15.8	40.9	17.2	73.9
	TF	14.8	40.4	16.4	71.6
Average		**15.9**	**41.6**	**17.0**	**74.5**

Table 6.1 shows that the house designs with a 3.6 star rating have similar heating and cooling energy as well as total operational energy requirements. The house designs with 3.9 star rating also have similar operational energy requirements. This is expected, because the designs were constrained to achieve the same star rating. All the houses with 3.9 star roof assemblages consumed significantly less annual operational energy than the houses of 3.6 star designs, as expected, because of their thicker insulation and roofing types. On average, energy requirements were reduced by 10%, 9% and 8% for heating, cooling and total, respectively, when the star rating was increased from 3.6 to 3.9 stars.

The LCA results are discussed in the next section.

6.2.1.2 LCA results

The LCA results are given in Table 6.2 for the case study house and house designs with 8 different roof assemblages for 4 selected life cycle impact category indicators.

Table 6.2: LCA results for the 3.6 and 3.9 star house designs - roof assemblages

	House Name	Construction	Operation	Maintenance	Disposal	Total
GHG (Tonne)						
3.6 Star	BC	26.0	48.0	6.43	-4.14	76.3
	MR	27.1	44.8	5.14	-4.22	72.8
	SF	26.9	45.5	5.07	-4.04	73.4
	SP	26.5	45.4	5.08	-4.22	72.8
	TF	25.9	44.8	5.14	-4.20	71.7
	Average	**26.5**	**45.7**	**5.37**	**-4.16**	**73.4**
	%	**36.1**	**62.2**	**7.31**	**-5.67**	**100**
3.9 Star	MR	29.1	40.3	5.14	-4.22	70.3
	SF	27.4	41.4	5.07	-4.04	69.9
	SP	29.3	41.6	5.08	-4.22	71.7
	TF	26.9	40.4	5.14	-4.20	68.2
	Average	**28.2**	**40.9**	**5.10**	**-4.17**	**70.0**
	%	**40.2**	**58.4**	**7.29**	**-5.96**	**100**
Cumulative Energy Demand (GJ)						
3.6 Star	BC	378	560	127	13.8	1080
	MR	394	524	108	12.9	1040
	SF	391	531	106	13.3	1040
	SP	388	528	106	12.8	1030
	TF	377	524	108	13.0	1020
	Average	**386**	**533**	**111**	**13.2**	**1040**
	%	**36.9**	**51.1**	**10.6**	**1.26**	**100**
3.9 Star	MR	415	469	108	12.9	1000
	SF	396	484	106	13.3	999
	SP	416	484	106	12.9	1020
	TF	387	469	108	13.0	980
	Average	**404**	**476**	**107**	**13.0**	**1000**
	%	**40.4**	**47.7**	**10.7**	**1.30**	**100**
Water Use (kL)						
3.6 Star	BC	1940	65.4	1090	-0.41	3100
	MR	1330	60.6	1070	-0.05	2460
	SF	1340	61.6	1070	-0.44	2470
	SP	1330	61.9	1070	-0.09	2460
	TF	1940	60.6	1070	-0.31	3070
	Average	**1580**	**62.0**	**1070**	**-0.26**	**2710**
	%	**58.1**	**2.29**	**39.6**	**-0.01**	**100**
3.9 Star	MR	1370	55.1	1070	-0.05	2500
	SF	1350	56.1	1070	-0.44	2470
	SP	1390	56.5	1070	-0.07	2520
	TF	1970	55.2	1070	-0.31	3090
	Average	**1520**	**55.8**	**1070**	**-0.22**	**2650**
	%	**57.4**	**2.11**	**40.4**	**-0.01**	**100**
Solid Waste (Tonne)						
3.6 Star	BC	3.86	1.63	4.95	70.3	80.8
	MR	4.17	1.51	4.94	64.7	75.4
	SF	4.07	1.54	4.94	64.6	75.2
	SP	4.08	1.54	4.94	64.7	75.3
	TF	3.86	1.51	4.94	71.9	82.2
	Average	**4.01**	**1.55**	**4.94**	**67.3**	**77.7**
	%	**5.15**	**1.99**	**6.36**	**86.5**	**100**
3.9 Star	MR	4.17	1.38	4.94	64.9	75.4
	SF	4.07	1.40	4.94	64.7	75.1
	SP	4.08	1.41	4.94	64.9	75.4
	TF	3.86	1.38	4.94	72.1	82.2
	Average	**4.04**	**1.39**	**4.94**	**66.7**	**77.0**
	%	**5.25**	**1.81**	**6.41**	**86.5**	**100**

In all cases, the same impact categories were dominated by the same life cycle stages. For example, for all designs, the majority of GHG emissions and CED occurred during the construction and operation phase, the water use was during construction and maintenance, and the solid waste was produced during the disposal phase. This is similar to the findings for the wall assemblages, as discussed in Section 5.2.1.2 and the findings of the similar study by Carre (2011).

GHG: On average, the construction and operation phases contributed the bulk of the emissions (99%), as for the case study house. The level of emissions across the whole life cycle varied only 9% from best to worst design. Varying the rooftop materials had no significant effect on the GHG levels over building whole life cycle, so the effect of changing the roof top materials was relatively small.

The effect of star rating was also not significant. The designs with 3.9 star rating had slightly higher GHG emissions overall (5%), also higher in the construction phase (6%), and lower in the operation phase (11%) compared to 3.6 star rating designs. This is equivalent to a decrease in GHG emissions of 15% per star rating increase. This result is comparable to those of Australian studies, where GHG emissions increased as star rating decreased. Carre (2011) reported a range 9-17% per star rating decrease.

CED: On average, 88% of CED impacts occurred during the construction and operations phase, similar to the Australian study by Carre (2011). Overall, the effect of rooftop material was not significant: the variation was only 6% from best to worst design, as for GHG.

The effect of star rating was also not significant. Overall, CED decreased only 4% when star rating increased from 3.6 to 3.9 stars. It also increased slightly in the construction phase (5%) and decreased significantly in the operation (11%), when the star rating increased by 0.3 stars. This is equivalent to a decrease in CED of around 13% per star rating increase. This result is comparable to Australian studies by Iyer-Raniga & Wong (2012), who reported the CED decreased as the star rating increased for various heritage buildings. One of their results show: CED decreased by around 18% when star rating increased from 2.3 to 3.3 stars.

Water use: On average, 98% of water use occurred during the construction and maintenance phases, similar to findings for the case study house and the houses with various wall assemblages (Chapter 5). Overall, these findings are also similar to Australian study by Carre (2011).

Changing the rooftop material had a significant effect on the water usage. Across the whole life cycle, it varied by 26% from best (metal and skillion) to worst (base case and tile) design. Construction had the largest contribution to the whole life cycle variation: the tiled roof designs had 30% higher water usage than the metal designs. This reflects that tile manufacturing consumes more water than sheet metal.

The effect of star rating was not significant. This result is comparable to recent Australian study by Iyer-Raniga & Wong (2012). One of their results show: star rating had no significant effect on water usage.

Solid waste: On average, 87% of solid waste was generated during the disposal phase, similar to the case study house and the houses modified with wall assemblages, as described in Chapter 5. Carre (2011) reported that disposal contributed the most to solid waste, but found a lower fraction of waste was generated during disposal (54-67%), as discussed in section 4.7.3. The differences are attributable to the differences in disposal scenario: this study assumed all waste goes to landfill, whilst Carre assumed some waste was recycled or reused.

The effect of changing the rooftop material within similar star rating was not significant. Across the whole life cycle, it varied by only 8% from best (metal) to worst (tiled) house design.

The effect of star rating was also not significant. There are a few studies that have looked at solid waste (Carre 2011; Kahhat et al 2009; Lippike et al 2004), but none of these considered the effect of different star ratings on solid waste.

In summary, rooftop material had no significant effect on the selected impact categories except for water usage. The tiled roof assemblage consumed significantly more water than a metal or skillion roof. The effect of star rating was insignificant on all impact categories. The star rating change of just 0.3 was too small to have a significant effect.

6.2.1.3 LCC results

The life cycle costs of the house designs with 3.6 and 3.9 star ratings and various roof assemblages are presented in Table 6.3. All the costs are calculated in Australian dollars.

Table 6.3: Life cycle cost ($) of the 3.6 and 3.9 star house designs - roof assemblages

House Name	Construction	Operation	Maintenance	Disposal	Total
BC	129000	20300	54000	5600	209000
MR 3.6	129000	19900	54000	6500	210000
SF 3.6	128000	20200	53000	6900	208000
SP 3.6	128000	20000	53000	6400	207000
TF 3.6	129000	19900	54000	6500	210000
Average	129500	18025	53500	6700	207750
MR 3.9	131000	17800	54000	6700	209000
SF 3.9	128000	18400	53000	6900	207000
TF 3.9	130000	17900	54000	6700	208000
SP 3.9	129000	18000	53000	6500	207000
Average	128600	20060	53600	6380	208800
Overall (%)	61.9	9.3	25.7	3.1	100

The results show that on average, construction and maintenance contributed the most to the total cost (88%), similar to the costs for the house designs with various wall assemblages, discussed in Section 5.3.1. Operational energy and disposal costs contributed by a relatively small amount.

The effect of star rating on LCC was negligible, except on operational costs. A small investment in construction costs of around $1000 (0.7%) was enough to improve the star rating from 3.6 to 3.9 stars and reduce the operation cost by approximately $2000 (11.3%). Hence, the total life cycle cost reduced around $1000 (0.5%). This is equivalent to a decrease in LCC of $3500 (1.6%) per star rating increase. These findings are similar to other recent Australian studies. One reported a reduction in LCC (of around $1300) when star rating of a house was increased from 5 to 6 stars (Moore & Morrissey 2010). Others reported that a small increase (1-2%) in initial costs improved star rating from 4 to 5 star (Belusko & O'Leary 2010; McLeod & Fay 2011). The small differences may be attributed to differences in model assumptions. Table 6.4 shows the percentage difference in costs for the various life cycle stages for the house designs with 3.6 and 3.9 star ratings and various roof assemblages.

Table 6.4: Differences (%) in LCC for 3.6 and 3.9 star rating house designs - roof assemblages

House Name	Construction	Operation	Maintenance	Disposal	Total
BC	0%	0%	0%	0%	0%
MR3.6	0%	-2%	0%	1%	0%
SF3.6	0%	-1%	-2%	8%	0%
SP3.6	-1%	-1%	-1%	0%	-1%
TF3.6	0%	-2%	0%	0%	0%
MR3.9	2%	-12%	0%	4%	0%
SF3.9	0%	-9%	-2%	6%	-1%
SP3.9	0%	-9%	-1%	1%	-1%
TF3.9	1%	-12%	0%	3%	-1%

The results show that the changing the roof assemblage had no significant effect on LCC: all the designs have similar total life cycle costs (within 1% variation). The effect of star rating on LCC is also negligible, except on operational costs, which decreased (by around 12%) when the star rating increased from 3.6 to 3.9 stars.

In summary, across the whole life cycle, LCC of house designs are not sensitive to changes in rooftop materials or star ratings. Significant savings in operational energy costs can be made by improving the star rating of the roof assemblage, for a negligible increase in construction costs.

In the following section, all the 3.6 and 3.9 star rating house-roof designs are analysed graphically to identify the best designs using single and multi-objective analysis approaches.

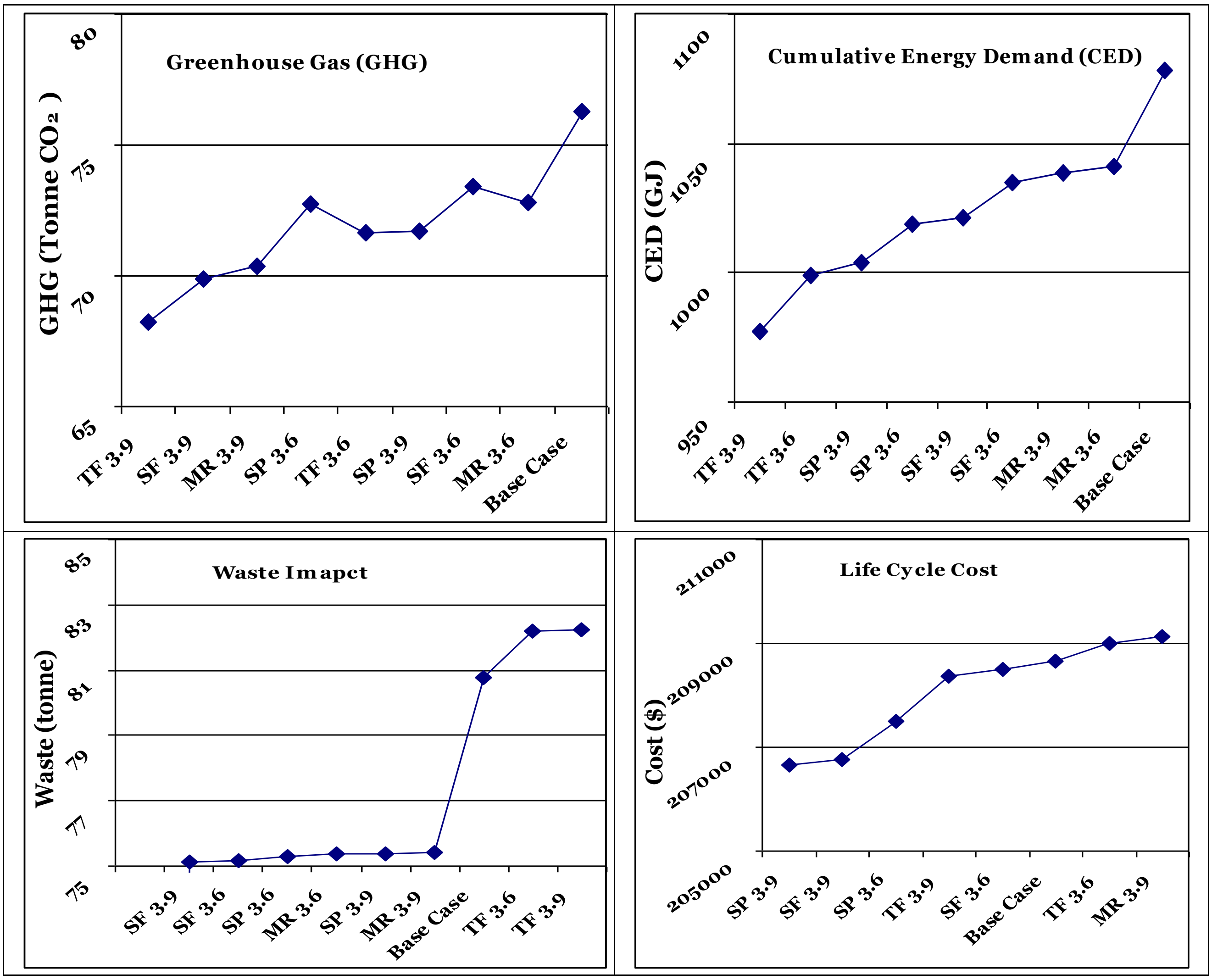
6.3 GRAPHICAL ANALYSIS OF ALL THE HOUSE DESIGNS: ROOF ASSEMBLAGES

In the following discussion, first a single then multi-objective function are used to identify the “best” or set of optimum designs for all the houses with 3.6 and 3.9 star roof designs.

6.3.1 Single-objective approach: roof assemblages

The effects of roof design on three major environmental impacts and life cycle cost indicators are shown in Figure 6.1.

Figure 6.1: GHG, CED, waste and LCC for the house designs with various roof assemblages



The house with low impact value is the best for all four indicators. It can be seen that the "best" design and ranking of roof assemblages is different for each impact category. For GHG and CED, the best design is the 3.9 star gable tile roof (TF3.9). On the other hand, for waste impact, the worst design is the same TF3.9. It has a cost close to mid-range. Hence, a single-objective approach can identify an optimum design for one indicator only, similar to the findings in Chapter 5. In a single-objective approach, the focus is too narrow to find an optimum design that has minimal environmental impact. Therefore, taking a single-objective approach is ineffective in identifying the best design, as the optimum depends on which variable is considered.

6.3.2 Multi-objective approach: roof assemblages

In this section, a multi-objective approach is used to identify the optimum design or set of designs, with two or more objective functions, similar to the approach taken for wall assemblages (Section 5.4.2).

6.3.2.1 Multi-objective approach (2 variables)

If a multi-objective approach is taken, two or more objective functions at a time can be minimised. In this section, a multi-objective approach is used to identify the optimum design, with just two objective functions.

Figure 6.2: Operation and construction costs of the 3.6 and 3.9 star house designs-roof assemblages

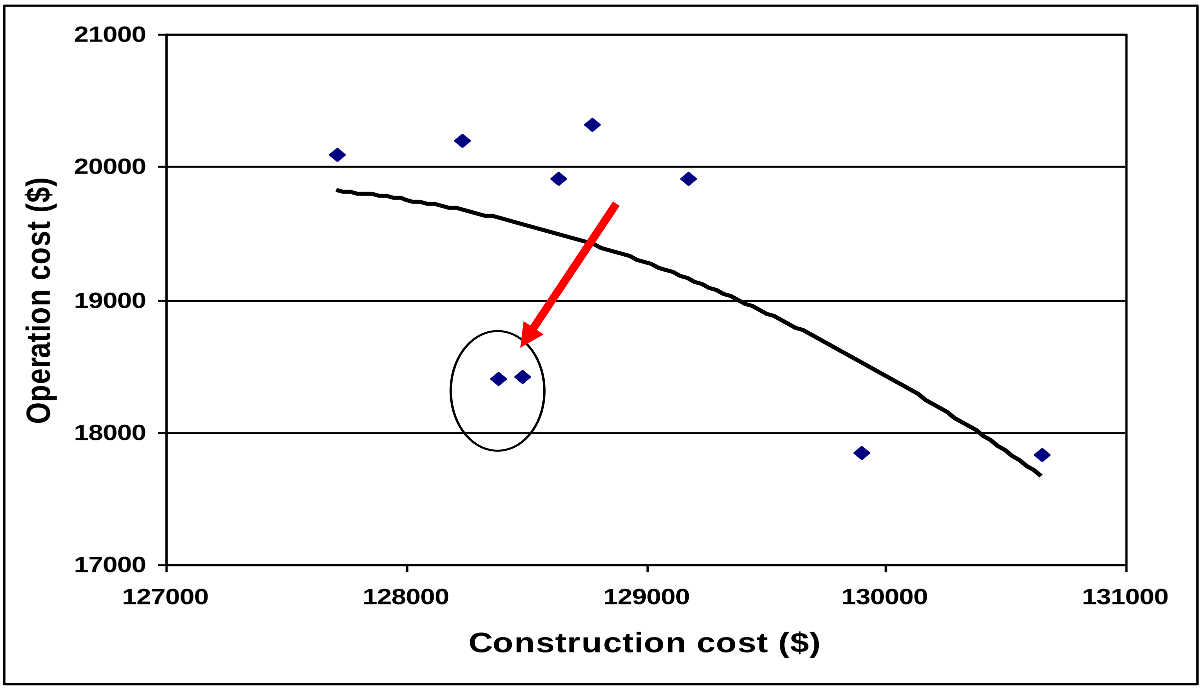


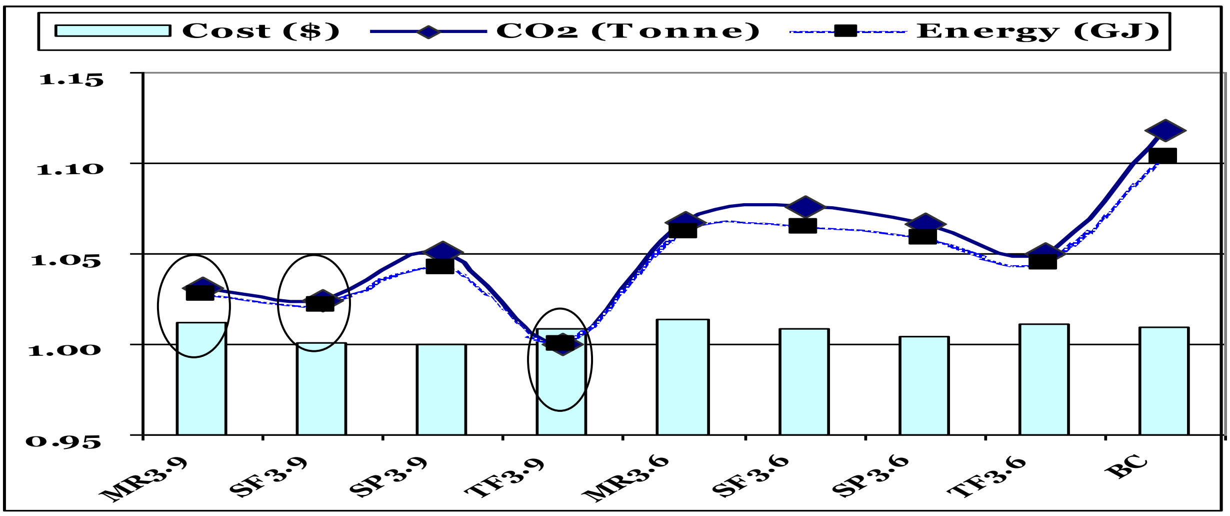
Figure 6.2 shows a two variable multi-objective approach for operation and construction costs. The figure shows there are two good designs (ringed). These are both 3.9 star designs, one with a skillion flat and the other skillion pitch roof. These have both low operation and construction costs. These do not have the lowest operation or construction cost, but they have the best trade-off.

If a different pair of indicators was chosen, the outcome might be the same or different, as observed in Section 5.4.2.1. For CED and construction costs, the outcome is the same, as GHG and CED follow the same trends. For construction costs and maintenance cost, the best design is SP3.6. Hence, this approach is also ineffective in identifying the best design, as the optimum depends on which variables are considered.

6.3.2.2 Multi-objective approach (multi variables)

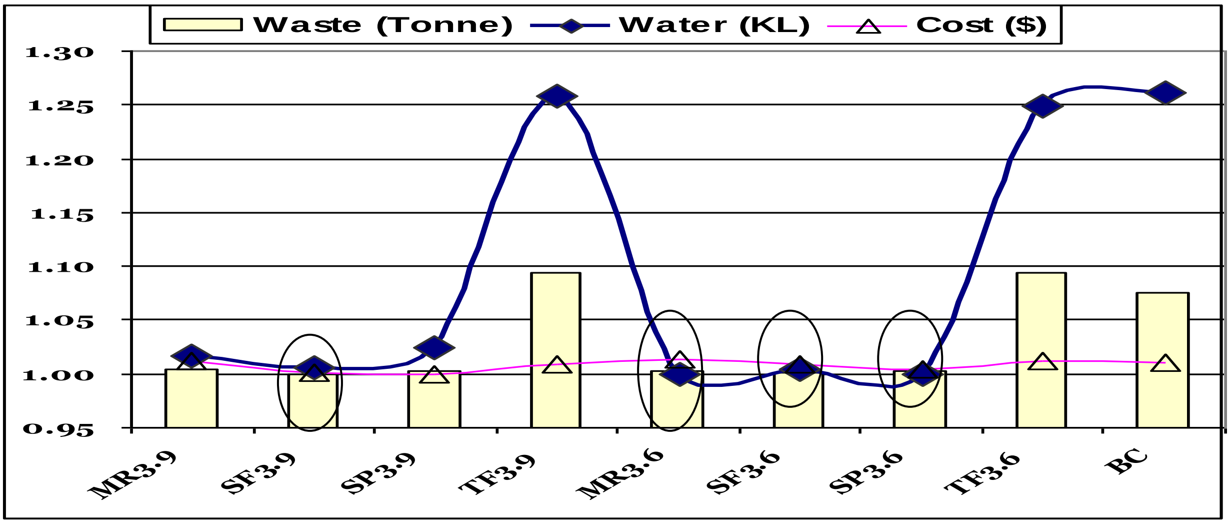
If a broader approach is taken, the whole of life cycle assessment across a range of impact categories as well as life cycle cost can be considered. Figure 6.3 and Figure 6.4 show a three variable multi-objective approach, with results for all 9 house designs with different roof assemblages. Global categories (CED and GHG) and life cycle costs are shown in Figure 6.3. Regional categories (water use and solid waste) and life cycle costs are shown in Figure 6.4. Normalised data are shown. The best designs have values close to unity with minimal spread: that is, all objective functions are minimised. These datasets show that there are several good designs (ringed). These give a better performance across a range of categories.

Figure 6.3: Normalised LCC and LCA result for global categories



For global categories (Figure 6.3), the optimum set of roof designs are higher star designs TF3.9. For regional impact categories, the optimum set of roof designs are both 3.6 and 3.9 star designs. For global categories, TF3.9 is the best design, but it is one of the worst for regional categories.

Figure 6.4: Normalised LCC and LCA result for regional categories



The optimum roof assemblage depends on the impact indicators. For global impact categories, the better designs are metal, gable tile and skillion flat. For regional impact categories, the optimum set of roof designs are a different set: metal, skillion flat and skillion pitch. Overall SF3.9 looks an attractive trade-off. However, it is clear that a graphical approach has limitations. It is difficult to interpret the best design when there are five objective functions. Therefore, a better approach is needed. A Mathematical Programming model will be used to assess whether it can identify the best design/s, discussed in Chapter 8.

A summary of results using different approaches is given in the next section.

6.3.3 Comparison of optimisation results: roof assemblages

Table 6.5 shows a comparison of results when different approaches were taken to identify the best design. The results show that there was no unique answer. The best design depended on which approach was taken and which objective functions were selected.

Table 6.5: Comparison of results using different evaluation approaches

Approach	Objective functions	Star rating	Best design
Single-objective	GHG, CED	Higher	Gable Tile (TF)
Single-objective	LCC	Higher	Skillion pitch (SP)
Multi-objective (two variables)	Operation cost and construction cost	Higher	Skillion flat (SF) Skillion pitch (SP)
Multi-objective (Three variables-global categories)	GHG, CED and LCC	Higher	Gable Tile (TF)
Multi-objective (Three variables-regional categories)	Water, waste and LCC	Lower	Skillion pitch (SP)
Multi-objective (all five variables)	GHG, CED, water, waste and LCC	Higher	Skillion flat (SF)

If construction and operation cost are minimised, there are two "best" design houses, SF3.9 and SP3.9. If multi objective functions are minimised, there is one best design, SF3.9.

6.4 SUMMARY

Rooftop material had no significant effect on the environmental impact categories except for water usage. Star rating had no significant effect on any categories. The star rating increase from 3.6 to 3.9 stars was too small to have a significant effect. LCC was also not sensitive to changes in rooftop materials or star rating. However, significant savings in operational energy costs can be made by improving the star rating of the roof assemblage, for a negligible increase in construction costs.

Single or multi-objective analysis identified an optimum design/s, depending on which objective functions was considered. If there are a wide range of house designs and objective functions, a graphical approach may fail to identify an optimum design. To find the optimum design mathematically, an optimisation algorithm must be used, presented in Chapter 8.

Evaluation of the effect of different floor assemblages on LCA and LCC is also needed to get a full picture for a whole building. The results of floor assemblage designs are presented in Chapter 7.

CHAPTER 7: FLOOR ASSEMBLAGE DESIGN

Introduction; Effect of floor assemblage design on LCA and LCC; Graphical analysis of all the house designs: floor assemblages; Summary

7.1 INTRODUCTION

In this chapter, the results for the LCA and LCC of floor assemblage designs are presented. The results were derived using the model and assumptions described in Chapters 3 and 4. The effects of selected alternative floor designs are evaluated. The case study house was used as the base case for the houses with alternative floor assemblages. In this chapter, only floor assemblage designs are varied while wall and roof assemblages are kept the same as the base case, similar to the approach undertaken for wall assemblage designs (in Chapter 5) and roof assemblage designs (in Chapter 6). The results are analysed for the whole building on a whole of life cycle basis.

The alternative floor assemblage designs presented in this chapter vary in floor top materials, type and position of insulation, and air gap thickness and position. Each design is varied such that it achieves maximum star rating, for example, by varying floor top materials with adding slightly thicker insulation in the first floor. The limiting factors for all the floor designs were best practice approach to meet BCA guideline. The floor tops selected for analysis are typical of the Australian building industry. A concrete slab on ground floor was the only floor type considered in this study. The reason for evaluating this floor type is that the case study house has a concrete slab grade design and many other studies have compared concrete slab with other floor types such as the popular suspended timber floor (Carre 2011; Lee, Featherstone & Robinson 2006; Lippike et al 2004). The economic and environmental impact of these modified floors on the building's whole life cycle is presented first, considering both an LCA and LCC approach. Then the optimum floor designs are identified using a graphical approach.

7.2 EFFECT OF FLOOR ASSEMBLAGE DESIGN ON LCA AND LCC

This section reports how different designs of floor assemblages affect life cycle environmental impact and life cycle cost over the various building life cycle stages. The chosen floor assemblage designs were selected from those available in *AccuRate*. Four floor tops were compared with the base case: carpet, timber, tiles, and “mixed”. In the mixed floor top, tiles and timber were combined.

Different from wall and roof designs, the floor assemblage designs were not constrained in same star rating. The different floor tops had different star rating limitations so that a common range could not be found. The maximum possible star rating with carpet was 3.6 stars while the maximum for tiles was 4.3 stars. Therefore, the assemblage designs have a different floor top and star rating for each alternative floor (the ground floor was not considered to have any insulation). The details for each assemblage design are described in Section 4.3.1.

7.2.1 Results for various star rating houses-floor assemblages

The annual operational energy requirements for heating and cooling were estimated as MJ/m^2.annum basis. The operation energy loads were then multiplied by the conditioned floor area and building life span to estimate the full life cycle energy input. The life cycle energy was used as data in the LCA model using *SimaPro* software, as in Sections 4.6.1 and 6.2.1. In this section the assemblage designs are abbreviated as follows: base case (BC), carpeted floor house (CFH), ceramic tiles floor house (CTH), timber floor houses (TFH), and mixed floor house (MFH).

7.2.1.1 Operational energy results

The operational energy requirements of the case study house and the house designs with alternative floor assemblages are shown in Table 7.1.

Table 7.1: Rated energy requirements of the houses with various floor designs

House options		**Heating and cooling energy**			**Total Annual Energy**
House name	Star rating	Heating	Cooling-sensible	Cooling-latent	MJ/m^2.annum
Base Case (BC)	3.6	18.2	46	17.3	81.5
Carpet (CFH)	3.6	16.8	45.8	17.8	80.4
Tiles (CTH)	4.3	16.4	32.3	16.5	65.2
Timber (TFH)	4.1	15.6	37.3	17.1	70.0
Mixed floor (MFH)	4.4	15.6	37.4	16.5	62.9

The results show that the total energy requirement varies significantly from best (mixed floor) to worst (base case) by 23%, as the star rating varies (from 3.6 to 4.4 stars). Hence, changing the floor top material in conjunction with slightly thicker insulation in first floor influenced the operational energy requirements (star rating) significantly. Similar values for changes in energy requirements as star rating changes have been published in the literature, ranging from 20 to 25% (DSE 2007) to 10% (Delsante 2007). Lee, Featherstone & Robinson (2006) reported a different result, that installing floor insulation in a floor assemblage may decrease the star rating in a hot climate like Brisbane, similar to this study.

The different outcome compared to this study may be attributed to differences in assemblage design: their study used floor insulation while no insulation was used in ground floor designs in this study. The results for the life cycle assessment are discussed in next section.

7.2.1.2 LCA results

The results for the selected life cycle impact category indicators are given in Table 7.2, showing three significant figures.

Table 7.2: Life cycle impacts for house designs with various floor assemblages

GHG (Tonne)					
House Name	Construction	Operation	Maintenance	Disposal	Total
Base Case (BC)	26.0	48.0	6.43	-4.21	76.2
Carpet (CFH)	26.1	45.3	8.49	-3.43	76.5
Tiles (CTH)	26.9	36.1	7.57	-3.42	67.1
Timber (TFH)	26.0	39.2	7.72	-4.14	68.8
Mixed floor (MFH)	26.0	35.0	7.57	-3.42	65.1
Average %	**37.0%**	**57.5%**	**10.6%**	**-5.24%**	**100%**
Cumulative Energy Demand (GJ)					
House Name	Construction	Operation	Maintenance	Disposal	Total
Base Case (BC)	378	560	127	13.0	1080
Carpet (CFH)	388	527	164	13.6	1090
Tiles (CTH)	399	427	136	13.6	970
Timber (TFH)	378	459	145	13.8	1000
Mixed floor (MFH)	378	412	136	13.6	940
Average %	**37.8%**	**46.9%**	**13.9%**	**1.34%**	**100%**
Water Use (kL)					
House Name	Construction	Operation	Maintenance	Disposal	Total
Base Case (BC)	1940	65.4	1090	0.29	3100
Carpet (CFH)	1980	61.9	1240	-0.23	3280
Tiles (CTH)	1970	47.5	1100	-0.23	3110
Timber (TFH)	1940	52.9	1120	-0.41	3110
Mixed floor (MFH)	1940	46.6	1100	-0.23	3090
Average %	**62.2%**	**1.75%**	**35.9%**	**-0.01%**	**100%**
Solid Waste (tonne)					
House Name	Construction	Operation	Maintenance	Disposal	Total
Base Case (BC)	3.86	1.63	4.95	70.3	80.8
Carpet (CFH)	3.53	1.54	5.29	70.0	80.3
Tiles (CTH)	3.54	1.19	5.20	70.9	80.8
Timber (TFH)	3.86	1.32	4.96	70.3	80.5
Mixed floor (MFH)	3.86	1.16	5.20	70.9	81.1
Average %	**4.62%**	**1.70%**	**6.35%**	**87.3%**	**100%**

In broad terms, all the designs have the similar types of impacts at different life stages, similar to the results for the house designs with various wall assemblages (Section 5.2.1.2) and roof assemblages (Section 6.2.1.2). The categories of GHG and CED are dominated by the construction and operation phases, water usage is dominated by the construction and maintenance phases, and solid waste is dominated by the disposal phase.

GHG: Table 7.2 shows that for the category of GHG, on average, construction contributed 37%, operations 57%, maintenance 11%, and disposal -5% of the emissions. The high level of emissions during construction were mainly from manufacture of construction materials; during operation, the emissions were from heating and cooling energy; during maintenance, the emissions were from material replacement, repainting and renovated material disposal; and during disposal, the negative emissions were from carbon sequestration of timber in landfill, as similar trend discussed in section 4.7.2.

GHG emissions varied significantly (by 17%) from best (mixed) to worst (carpet) floor assemblage design. Low GHG emissions correlated with high star rating, as expected, similar to the results for wall and roof assemblage design, discussed in Chapters 5 and 6. There was no significant effect of design on GHG emissions during construction: it varied by only 4% from best to worst designs. During operation, maintenance and disposal life phases, there was significant variation in GHG with floor design, of 37%, 20% and 17%, respectively. For higher star rating designs, GHG emissions were lower during the operation life phase, as expected, as the star rating reflects a building with lower annual energy requirements. Variation of GHG emissions for the maintenance life phase was attributed to the schedule for floor top replacement: carpet was modelled as needing replacement every 10 years, while tiles and timber were replaced only every 25 years. The variation in GHG emissions during the disposal life phase correlated with the volume of wood used in the assemblage: the more wood, the higher the carbon sequestration benefit, the lower the GHG emissions.

There are a few LCA studies of floor assemblage design. However, most studies compare concrete slab with suspended timber floors (Carre 2011; Lippike et al 2004) rather than with changes of floor tops. Some other studies have also found that carpet had a higher GHG emission than other floor coverings (Bowyer et al 2009 and Peterson & Solberg 2005) that is attributed to the high-energy consumption during manufacture and use of the carpet.

In summary, GHG emissions varied significantly with floor assemblage design. House designs with a mixed floor top were superior to carpet. The higher the star rating the lower the GHG emissions, as expected.

CED: Table 7.2 shows that the construction and operation phases contributed the bulk of the impact (85%). Overall, CED was significantly affected by floor assemblage design: it varied by 14% from best (mixed and tile) to worst (carpet). The higher star-rating designs had lower CED, as expected. This is mainly due to lower energy requirements during operation phase, where CED varied significantly from best to worst design, by 36%.

The CED also varied significantly from best to worse design during the maintenance life phase, by 17%. The variation in maintenance was due to the more frequent replacement of some floor tops than to others. In construction and disposal, the variation was not significant.

The literature is limited on the topic of variation of CED with floor top material. One study reported that timber had lower CED than linoleum and vinyl floor tops although they did not specify the star rating of house designs (Bowyer et al 2009).

In summary, CED varied significantly with floor assemblage design. House designs with a mixed floor top were superior to carpet. The higher star rating had a lower CED as expected. Maintenance was also lower, due to lesser use of material. The results were similar to the results for GHG emissions.

Water use: Table 7.2 shows that for the category of water use, on average, construction and maintenance contributed 98% of the impact. The high contribution to water use of the construction and maintenance life phases reflects the use of high water use components (plasterboard, timber), as discussed in Section 5.2.1.2.

Overall water use did not vary significantly with floor assemblage design: it varied less than 10% from best to worst design. However, it varied significantly during the maintenance life phase, by 11%, from best (mixed) to worst (carpet) design.

There are no similar studies in the literature to compare the water use effect from others.

Solid waste: Table 7.2 shows that for the category of solid waste, on average, disposal contributed 87% of the total impact. Overall, solid waste did not vary significantly with floor assemblage design: it varied less than 10% from best to worst design. The results for the life stages were similar: none showed a significant variation with floor design.

There are a few studies in the literature on the effect of floor assemblage design on solid waste generation of buildings. There is general agreement with this study that there is no significant effect of floor design on LCA impacts. Two studies reported that the effect of floor design on LCA is less than 1% (Kahhat et al 2009; Lippike et al 2004). Another reported the effect was less than 4% (Carre 2010).

In summary, the sensitivity of LCA to floor assemblage design depends on the impact category and the life phase. The categories of GHG, CED and water use in the maintenance life phase only, varied significantly with floor design. The best design was consistently the mixed floor tops, and the worst, carpet.

7.2.1.3 LCC results

Table 7.3 shows the LCC for house designs with various floor assemblages.

Table 7.3: LCC for house designs: various floor tops

House Name	Star rating	Construction ($)	Operation ($)	Maintenance ($)	Disposal ($)	Total ($)
BC	3.6	129,000	20,000	53,900	6,400	209,000
CFH	3.9	124,000	20,000	50,200	7,400	202,000
TFH	4.1	130,000	17,500	53,900	6,600	208,000
CTH	4.3	131,000	16,000	48,200	6,800	202,000
MFH	4.4	129,000	15,700	50,500	6,700	202,000

On average, construction contributed 63%, operation 9%, maintenance 27% and disposal just 3% of the total cost. The model system boundary excludes some items for which there was no reliable data, such as frequency and cost of carpet cleaning, and resealing of timber floors.

Table 7.4: Difference (%) in life cycle cost of alternative houses compared to base case

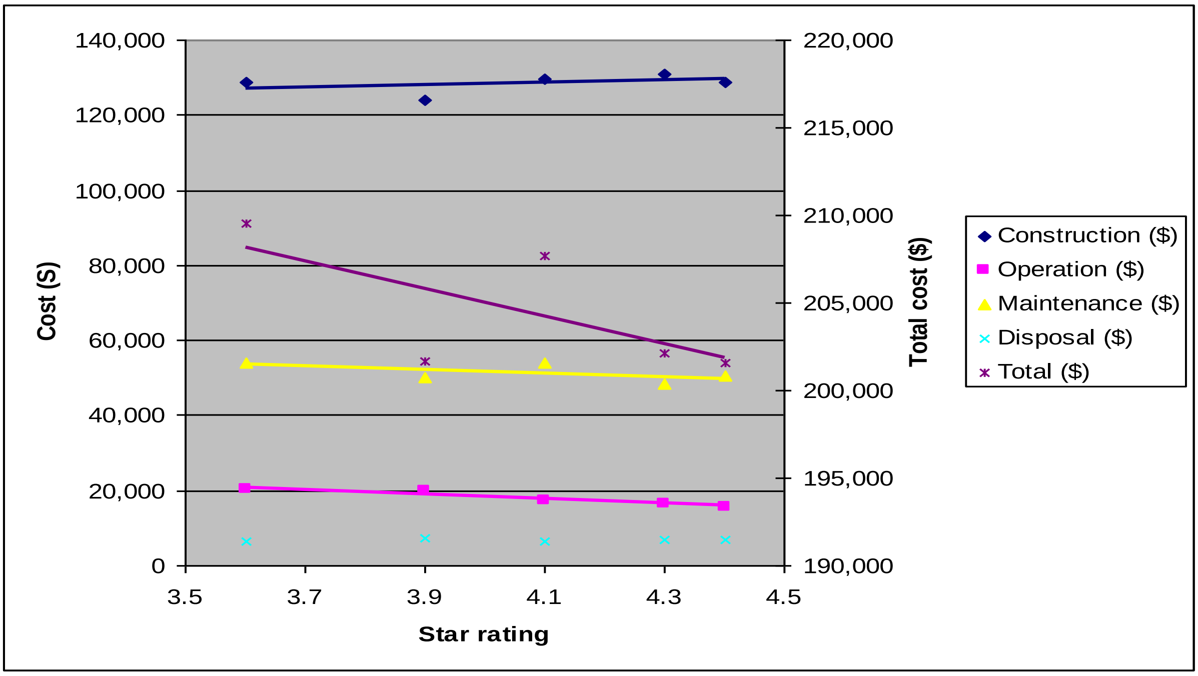
House Name	Star rating	Construction	Operation	Maintenance	Disposal	Total
BC	3.6	0%	0%	0%	0%	0%
CFH	3.9	-4%	-1%	-7%	15%	-4%
TFH	4.1	1%	-14%	0%	2%	-1%
CTH	4.3	2%	-20%	-11%	5%	-4%
MFH	4.4	0%	-23%	-6%	4%	-4%

Table 7.4 shows the difference between the whole house life cycle costs for the house designs with different floor tops and the base case house. Total and construction costs did not vary significantly with floor assemblage design even though star rating varied from 3.6 to 4.4 stars. The variation is less than 10% from best to worst designs. However, operation, maintenance and disposal costs varied significantly, with differences of 23%, 11% and 15%, respectively from best to worst design. These differences are discussed below.

7.2.1.4 Discussion

Figure 7.1 shows the variation of the costs of different life phases as the star rating is increased.

Figure 7.1: LCC costs for different life phases as a function of star rating



Construction costs increased by a small amount as star rating increased. The other life phases show the opposite trend. Total cost and operation decreased as star rating increased. Operation costs are expected to decrease with star rating, as the higher the star rating the lower the energy required maintaining comfort with heating and cooling. Maintenance costs for tiles are lower than timber; hence, the saving in maintenance as star rating increases. Disposal costs for carpet are higher as the carpet is replaced frequently, and the old carpet must be disposed of. Overall, there is no stand-out low costs design.

Table 7.5 shows estimates for the LCC for a range of star ratings, extrapolated from the best-fit line to the data presented in Table 7.3. A linear relationship is approximately true for the data shown in Figure 7.1. It will be a less accurate predictor of costs outside the study range, but can be used to gauge general trends.

Table 7.5: Estimates of costs for different life phases at a wide range of star ratings

Star rating	Construction	Operation	Maintenance	Disposal	Total
	($)	($)	($)	($)	($)
1	119617	37181	65690	6438	228925
2	122500	30900	61000	6550	220950
3	125384	24618	56311	6662	212974
3.5	126825	21477	53966	6717	208986
4	128267	18337	51622	6773	204998
4.5	129709	15196	49277	6829	201010
$/star rating	2900	-6300	-4700	100	-8000

The results show that for a modest increase in construction costs (about $2900 per star rating), operation and maintenance costs drop a larger amount, resulting in a net saving, so total costs also decrease. $2900 is 2.4% of construction costs.

There have been a number of LCC studies on residential buildings, as discussed in Section 2.5.4. A few have reported on the relationship between star rating and LCC, but none has reported on effect of assemblage design on LCC. McLeod & Fay (2011) reported that an additional 1-2% of initial (construction) cost might be required to improve a residential house design from a 4 to 5 star rating, similar to this study. Moore & Morrissey (2010) reported that total costs increased, by around $4200 per star rating, when the house design improved from 6 to 7 star rating. That is a significant increase compared to the modest decrease found in this study. This large difference in outcomes between the two studies may be attributed to different assumptions: the Moore & Morrissey study assumed discounting rate 3.5% over 0-30 years; 3% over 30-70 years, while this study assumed 6%. Another reason is that this study was modelled 3.6 star rating designs to 4.4 stars.

In summary, the result shows that the house designs with various floor tops have similar construction and total life cycle costs. However, operation, maintenance and disposal costs varied significantly from best to worse floor designs. The savings in operation and maintenance for designs with higher star ratings resulted in a lower total cost. No one design performed best across all the life phases, so there was no clear “best” design.

In the following section, the results for house designs with various floor tops are analysed graphically to identify the best design. Both single and multi-objective analysis approaches are used.

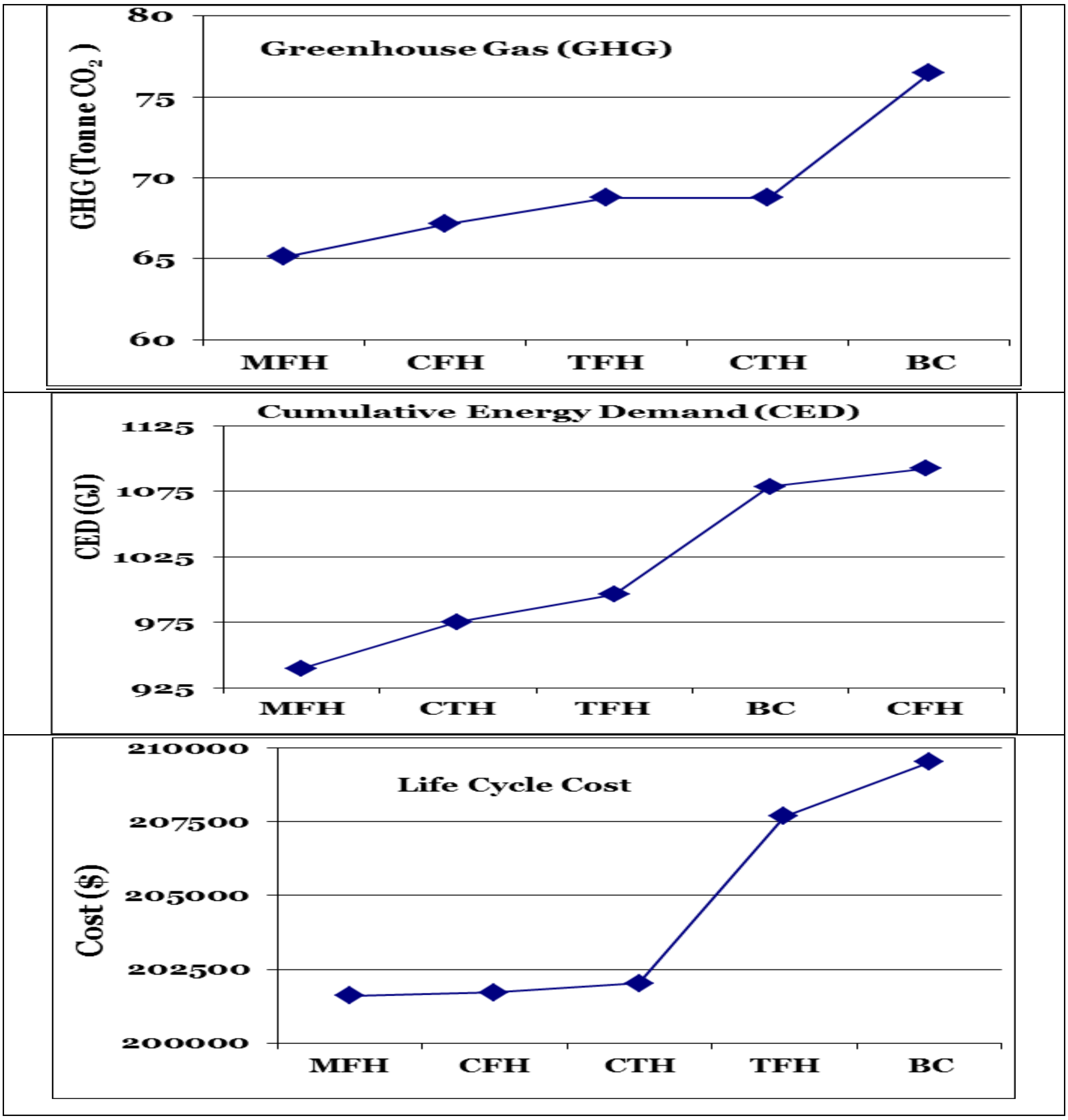
7.3 GRAPHICAL ANALYSIS OF ALL THE HOUSE DESIGNS: FLOOR ASSEMBLAGES

In the following discussion, first a single then a multi-objective functions are used to identify the "best" or set of optimum designs for all the houses of floor assemblages.

7.3.1 Single-objective approach: floor assemblages

Using a single-objective analysis, one objective at a time is minimised to identify the optimum. The results for two environmental impacts (GHG and CED) and for LCC are shown in Figure 7.2. Water and solid waste are not included, as they did not vary significantly with floor top, as discussed 7.2.1.2.

Figure 7.2: GHG, CED and LCC for the house designs with various floor assemblages

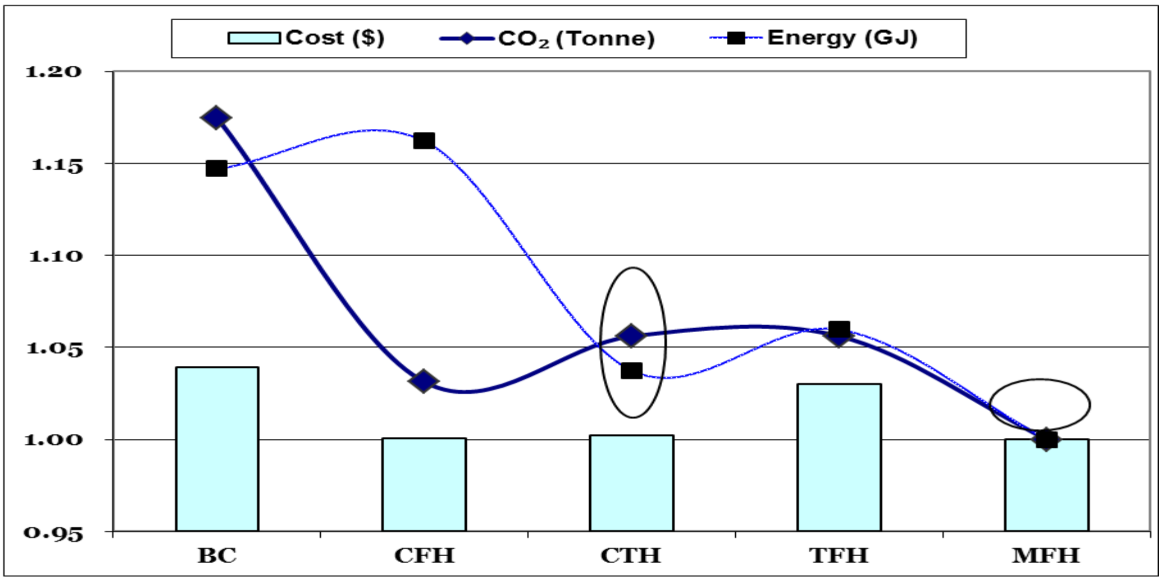


The results show that the "best" design is the mixed floor for the 3 indicators shown. The mixed floor had the highest star rating (4.4). The ranking of the other house designs depends on which indicator is selected. This is different to the results for wall and roof assemblages, where the "best" design depended on which indicator was selected. This reflects that in floor design, the star rating was not constrained, and so the designs had a wider range of star ratings (3.6 to 4.4) than for wall and roof designs (3.6 to 3.9). Hence, taking a single-objective analysis is effective here in identifying the best design, but generally the optimum will depend on which objective functions is considered, other things being equal.

7.3.2 Multi-objective approach: floor assemblages

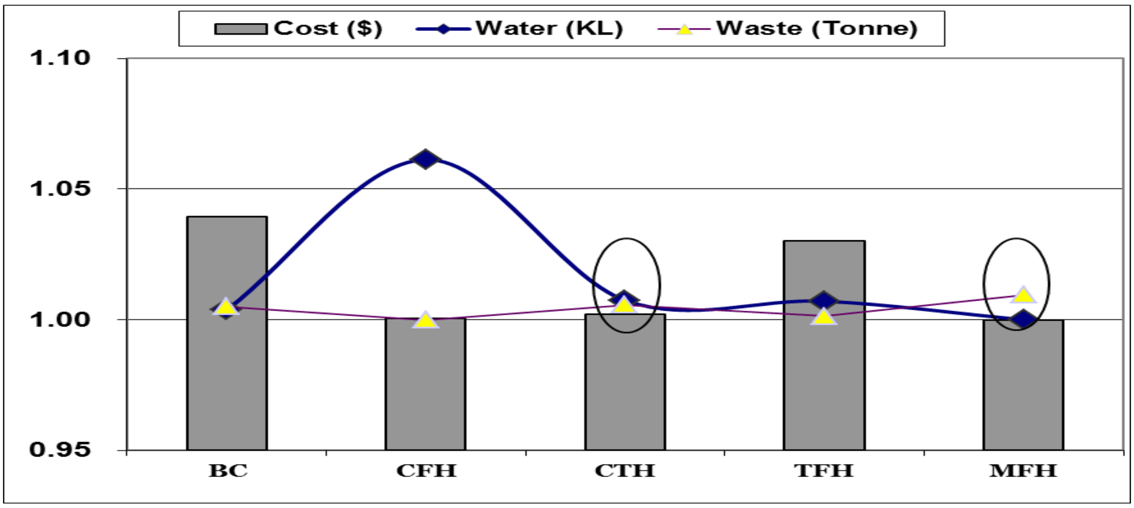
If a multi-objective analysis is taken, multiple objective functions can be minimised at the same time. Figure 7.3 and Figure 7.4 show a three variable multi-objective approach, for two environmental impacts and a life cycle cost. Normalised data are shown: the actual value is divided by the optimum value. The best designs have values close to unity with minimal spread: that is, all the objective functions are minimised.

Figure 7.3: Normalised LCC and LCA result for global categories



Global categories (CED and GHG) and life cycle costs are shown in Figure 7.3 and regional categories (water use and waste impacts) and life cycle costs are shown in Figure 7.4.

Figure 7.4: Normalised LCC and LCA result for regional categories



There are several optimal or close to the optimal designs (ringed), which provide good performance across a range of categories. However, the mixed floor is clearly the best design, as it has values close to unity for all variables. This is in agreement with the results for single-objective analysis. It is different to the outcomes for analysis of wall and roof assemblage designs, which again reflects the difference in assumptions about star rating, as discussed above.

7.4 SUMMARY

In summary, several LCA categories (GHG, CED, and water use) varied significantly with floor design. Several LCC costs (operation, maintenance and disposal) varied significantly with different floor tops, with higher constructions costs offset by savings in operation and maintenance as star rating increased, resulting in a small net saving. The outcome from both SOO and MOO approaches was that best floor assemblage design is the mixed floor (a combination of timber and tiles). The mixed floor also had the best star rating (4.4 stars). This outcome is different to that for wall and roof assemblages, where SOO and MOO approaches identified a different "best" design.

Chapter 8 presents approaches to find the best possible optimum house design mathematically when all assemblages are optimised. A linear-programming optimisation will be used to identify the best house design.

CHAPTER 8: MATHEMATICAL PROGRAMMING OPTIMISATION

Introduction; Optimisation of wall, roof and floor assemblage design using SOO; Optimisation of wall, roof and floor assemblage design using MOO; Comparison of case study and optimal house designs; Summary

8.1 INTRODUCTION

Several optimal designs were identified in Chapter 5, 6 and 7 using a graphical approach. This chapter presents results for optimisation of wall, floor and roof designs using a mathematical programming (MP) model. The MP model results are compared with the results obtained in Chapters 5, 6 and 7.

MP models take a range of forms, from single to multi-objective and from linear to nonlinear. The advantages of an MP model are that it can identify a single or range of optimum solutions using SOO and MOO approaches while imposing a set of constraints on some or all variables. A graphical approach can identify a range of optimum solutions but is limited in its ability to impose a set of constraints on some variables.

The interactive computer software package LINDO (Linear Interactive and Discrete Optimizer) was chosen for MP modelling in this study, as it is suitable for small size complex multi-objective optimisation, as discussed in Section 3.5.4 (Khan & Ardil 2009; Khan & Min-Allah 2011; Zacharia 2003). LINDO can be used to solve linear, integer and quadratic programming problems. The approach taken in this study was linear. Data from analysis of the life cycle impacts and costs of the various house designs were used as input data for the model. Four environmental impacts (i.e. GHG, CED, water use and solid waste) and life cycle costs were modelled as the objective functions. The MP model can maximise or minimise objective functions: in this study all objective functions were minimised. The life cycle impacts and costs of house designs were then optimised subject to various sets of constraints.

It is critical to set appropriate constraints (Wang 2005; Zacharia 2003). A suitable choice of constraints can provide a means of exploring a variety of “best” design (Zacharia 2003). The typical sets of constraints are highest or lowest values (Fonseca & Fleming 1998). Other constraints in house design might reflect stakeholder demands, such as, the house design must achieve a certain star rating or the construction costs must not exceed a certain budget. In this study, various sets of constraints were applied and the effects on the model outcomes were assessed. In this study, in addition to highest, lowest and average values, the base case data were used as a set of constraints for the objective functions. Conclusions are drawn about what is the most useful approach to identify optimum designs.

8.2 OPTIMISATION OF WALL, ROOF AND FLOOR ASSEMBLAGE DESIGNS USING SOO

In the following section, results are illustrated firstly for MP model optimisation of wall assemblage design, using four sets of constraint values, highest, lowest, average and base case. Secondly, results are illustrated for optimisation of roof assemblage design, and lastly for floor assemblage design, using two sets of constraints, highest and average. The results are compared to the results found using a graphical approach reported in Chapters 5, 6 and 7. Conclusions are drawn about the suitability of constraints for MP model optimisation.

8.2.1 MP model optimisation using SOO - wall designs

The results for MP model optimisation for the houses with 3.6 to 3.9 star rating wall assemblage designs are presented in Table 8.1 to Table 8.4 for constraints set to highest, lowest, average and base case data, respectively. A sample optimisation model and results of each constraint are given in Appendix 8.A to Appendix 8.D, shown GHG objective function case only.

Table 8.1: SOO results for optimisation of wall designs - “highest” constraints

Objective function to be minimised	Target constraints: all at least as good as the “highest”		“Best design”
GHG	CED (GJ)	≤1079	PL3.9
	Water use (kL)	≤3108	
	Solid waste (Tonne)	≤96.8	
	LCC (AUD)	≤245277	
CED	GHG (Tonne CO_2)	≤77.8	PL3.9
	Water use (kL)	≤3108	
	Solid waste (Tonne)	≤96.8	
	LCC (AUD)	≤245277	
Water Use	GHG (Tonne CO_2)	≤77.8	PL3.9
	CED (GJ)	≤1079	
	Solid Waste (Tonne)	≤96.8	
	LCC (AUD)	≤245277	
Solid Waste	GHG (Tonne CO_2)	≤77.8	WB3.6
	CED (GJ)	≤1079	
	Water use (kL)	≤3108	
	LCC (AUD)	≤96.8	
LCC	GHG (Tonne CO_2)	≤77.8	BC
	CED (GJ)	≤1079	
	Water use (kL)	≤3108	
	Solid Waste (Tonne)	≤96.8	

Table 8.1 summarises the results for optimisation using constraints set to the “highest” value. The highest value is the maximum impact or cost for any of the house designs. The highest constraint values are as follows: for GHG it was 77.8 tonne for house design BH3.7; for CED it was 1079 GJ for house design BH3.7; for water use, it was 3108 kL for design CH3.6; and for solid waste, it was 96.8 tonne for BH3.9. When this set of constraints is used, the number of designs that are considered is 19: the case study house and all the houses with modified wall designs (18).

The first optimisation result shown in Table 8.1 is for GHG. The MP model reduces this MOO problem to a SOO problem by optimising one objective function at a time. GHG is the first objective function to be minimised. The designs with minimum GHG has other impacts that must be less than their constraint values, but not necessarily minimised. This set of constraints provides the means to consider all designs as possible optimum designs.

The results show that there is no single “best” design that minimises all objective functions at the same time. The higher star rating pine saw log house design PL3.9 has the minimum GHG, CED and water use but not the minimum solid waste or LCC. The design that minimises solid waste is the lower star rating weatherboard house

WB3.6. The design that minimises LCC is the base case house. This outcome - a set of "best" designs - is similar to the results found with the graphical approach reported in Section 5.4.1. Firstly, using the highest values for constraints means that in effect no constraints are applied: all designs are considered, as was the case Section 5.4.1. Secondly, optimising one objective function without any effective constraint leads to a range of "best" solutions, similar to those reported in Section 5.4.1. The similarity of results from the two approaches supports the validity of the MP optimisation using a SOO approach.

Table 8.2: SOO results for optimisation of wall designs - "lowest" constraints

Objective function to be minimised	**Target constraints: all at least as good as the "lowest"**		**"Best" design**
GHG	CED (GJ)	≤1013	No feasible solution
	Water use (kL)	≤3068	
	Waste impact (Tonne)	≤78.2	
	LCC (AUD)	≤208656	
CED	GHG (Tonne CO_2)	≤65	No feasible solution
	Water use (kL)	≤3068	
	Waste impact (Tonne)	≤78.2	
	LCC (AUD)	≤208656	
Water Use	GHG (Tonne CO_2)	≤65	No feasible solution
	CED (GJ)	≤1013	
	Waste impact (Tonne)	≤78.2	
	LCC (AUD)	≤208656	
Solid Waste	GHG (Tonne CO_2)	≤65	No feasible solution
	CED (GJ)	≤1013	
	Water use (kL)	≤3068	
	LCC (AUD)	≤208656	
LCC	GHG (Tonne CO_2)	≤65	No feasible solution
	CED (GJ)	≤1013	
	Water use (kL)	≤3068	
	Waste impact (Tonne)	≤78.2	

Table 8.2 summaries the results for optimisation using constraints set to the "lowest" values. The lowest value is the minimum impact or cost for any of the designs. For example, the lowest value for GHG was 65 tonne for house design PL3.9, for CED was 1013 GJ for house design PL3.9, for water use was 3068 kL for house design PL3.9 and for solid waste was 78.2 tonne for house design WB3.6.

The first optimisation result shown in Table 8.2, is again for GHG. Now, the objective functions must be less than or equal to the lowest value for that particular objective function calculated for any design. In this case, the design with minimum GHG would have other impacts that are no higher than the lowest life cycle environmental impact and cost of any design. This set of constraints is so limiting that it does not allow consideration of any of the designs. The results show there is no feasible solution that minimises GHG and meets all the other lowest constraints. The results are similar for all the objective functions. This is the likely outcome for a MOO problem where the desirable solution is one that minimises each objective function. Hence, applying constraints set to the lowest value is not useful in this study.

Table 8.3: SOO results for optimisation of wall designs - "average" constraints

Objective function to be minimised	**Target constraints: all at least as good as the "average"**		**"Best" design**
GHG	CED (GJ)	≤1055	WB3.9
	Water use (kL)	≤3092	
	Waste impact (Tonne)	≤84.6	
	LCC (AUD)	≤218549	
CED	GHG (Tonne CO_2)	≤73.1	WB3.9
	Water use (kL)	≤3092	
	Waste impact (Tonne)	≤84.6	
	LCC (AUD)	≤218549	
Water Use	GHG (Tonne CO_2)	≤73.1	WB3.6/WB3.7
	CED (GJ)	≤1055	
	Waste impact (Tonne)	≤84.6	
	LCC (AUD)	≤218549	
Solid Waste	GHG (Tonne CO_2)	≤73.1	WB3.6/WB3.7
	CED (GJ)	≤1055	
	Water use (kL)	≤3092	
	LCC (AUD)	≤218549	
LCC	GHG (Tonne CO_2)	≤73.1	WB3.6/WB3.7
	CED (GJ)	≤1055	
	Water use (kL)	≤3092	
	Waste impact (Tonne)	≤84.6	

Table 8.3 summarises the results for optimisation using constraints set to the "average" values. The average value was calculated from the results for all of the designs. For example, the average value for GHG for all the house designs from 3.6 to 3.9 star wall designs was 73.1 tonne, for CED was 1055 GJ, for water use was 3092 kL and for solid waste was 84.6 tonne. In this case, the design with minimum GHG has impacts at least as good as the 'average' life cycle environmental impacts and cost of all designs. This set of constraints limits the range of designs to a small number (7) that have environmental impacts or cost at least as good as the average of life cycle environmental impacts and costs.

The results again show there is no single "best" design that minimises all objective functions at the same time. The higher star rating weatherboard house design WB3.9 has the minimum GHG and CED but does not have the minimum water use, solid waste or LCC. The designs that minimise water use, solid waste and LCC are WB3.6 and WB3.7. This is a "clean sweep" for weatherboard, but fails to identify the best star rating. Overall, the high star rating weatherboard design WB3.9 looks an attractive choice, as it is ranked in the top three for all the objective functions. WB3.9 was also found to be one of the optimal designs when a multiple objective functions was used with the graphical approach (section 5.4.2).

Table 8.4: SOO results for optimisation of wall designs-"base case" constraints

Objective function to be minimised	Target constraints: all at least as good as "base case"		"Best" design
GHG	CED (GJ)	≤1078	Base case
	Water use (kL)	≤3103	
	Waste impact (Tonne)	≤80.8	
	LCC (AUD)	≤208656	
CED	GHG (Tonne CO_2)	≤76.2	Base case
	Water use (kL)	≤3103	
	Waste impact (Tonne)	≤80.8	
	LCC (AUD)	≤208656	
Water Use	GHG (Tonne CO_2)	≤76.2	Base case
	CED (GJ)	≤1078	
	Waste impact (Tonne)	≤80.8	
	LCC (AUD)	≤208656	
Solid Waste	GHG (Tonne CO_2)	≤76.2	Base case
	CED (GJ)	≤1078	
	Water use (kL)	≤3103	
	LCC (AUD)	≤208656	
LCC	GHG (Tonne CO_2)	≤76.2	Base case
	CED (GJ)	≤1078	
	Water use (kL)	≤3103	
	Waste impact (Tonne)	≤80.8	

Table 8.4 summarises the results for optimisation using constraints set to the base case values. The value of GHG for the base case was 76.2 tonne, CED was 1078 GJ, water use was 3103 kL and solid waste was 80.8 tonne. In this case, the design with minimum GHG has impacts and cost at least as good as the base case's. This set of constraints provides a very limited range of designs to consider (one only – the base case) and leads to the trivial result that the base case would meet all the targets for optimal life cycle environmental impacts and costs. This is a good demonstration of

Zacharia's (2003) advice that it is critical to set appropriate constraints. Hence, applying constraints set to the base case is also not useful in this study.

In summary, outcomes from MP modelling using highest value of constraints and a graphical approach were similar, supporting the validity of the MP modelling approach. MP modelling identified optimum designs but these depended on which constraints were applied. Using lowest or base case values led to no feasible solution or a trivial solution, as they did not consider a wide enough range of design options. Using the highest and average constraints considered a suitable range of design options but failed to identify a single optimal solution, when all objective functions were considered. Weatherboard was the best cladding identified using average values as constraints, with the high star rating design WB3.9 ranked in the top 3 for each objective function. Further refinement of the model is needed to identify a single optimum design.

The optimisation results for the house designs with various roof assemblages are discussed in the next section.

8.2.2 MP model optimisation using SOO: roof designs

The results for MP model optimisation for the houses with 3.6 and 3.9 star roof designs are shown in Table 8.5 and Table 8.6 for constraints set to "highest" and "average" data, respectively. A sample model and results of each constraint are given in Appendix 8.E and Appendix 8.F, shown GHG objective function only. When the constraints are set to the highest values, the number of designs considered is 9: the case study house and all the houses modified with roof designs. When the constraints are set to the average values, the numbers of designs that are considered is 3.

Table 8.5: SOO results for optimisation of roof designs - "highest" constraints

Objective function to be minimised	**Target constraints: all at least as good as the "highest"**		**"Best" design**
GHG	CED (GJ)	≤1078	TF3.9
	Water use (kL)	≤3103	
	Waste impact (Tonne)	≤82.2	
	LCC (AUD)	≤209576	
CED	GHG (Tonne CO_2)	≤76.2	TF3.9
	Water use (kL)	≤3103	
	Waste impact (Tonne)	≤82.2	
	LCC (AUD)	≤209576	
Water Use	GHG (Tonne CO_2)	≤76.2	SP3.6
	CED (GJ)	≤1078	
	Waste impact (Tonne)	≤82.2	
	LCC (AUD)	≤209576	
Solid Waste	GHG (Tonne CO_2)	≤76.2	SF3.9
	CED (GJ)	≤1078	
	Water use (kL)	≤3103	
	LCC (AUD)	≤209576	
LCC	GHG (Tonne CO_2)	≤76.2	SP3.9
	CED (GJ)	≤1078	
	Water use (kL)	≤3103	
	Waste impact (Tonne)	≤82.2	

Table 8.5 shows that the higher star rating tile roof house design TF3.9 has the minimum GHG and CED. The lower rating skillion pitch roof house design SP3.6 and higher rating skillion flat roof house design SF3.9 have the minimum water use and solid waste, respectively. The higher star rating skillion pitch roof house design SP3.9 has the minimum LCC. Again, there is no single "best" design when all objective functions are considered, similar to the results using a graphical approach (Section 6.3.1). Again, this is expected, because all designs were considered in both cases. The similarity of results from the two approaches again supports the validity of the MP optimisation using SOO approach.

Table 8.6: SOO results for optimisation of roof designs - "average" constraints

Objective function to be minimised	Target constraints: all at least as good as the "average"		"Best" design
GHG	CED (GJ)	≤1023	SF3.9
	Water use (kL)	≤2682	
	Waste impact (Tonne)	≤77.4	
	LCC (AUD)	≤208237	
CED	GHG (Tonne CO_2)	≤71.9	SF3.9
	Water use (kL)	≤2682	
	Waste impact (Tonne)	≤77.4	
	LCC (AUD)	≤208237	
Water Use	GHG (Tonne CO_2)	≤71.9	SF3.9
	CED (GJ)	≤1023	
	Waste impact (Tonne)	≤77.4	
	LCC (AUD)	≤208237	
Solid Waste	GHG (Tonne CO_2)	≤71.9	SF3.9
	CED (GJ)	≤1023	
	Water use (kL)	≤2682	
	LCC (AUD)	≤208237	
LCC	GHG (Tonne CO_2)	≤71.9	SF3.9
	CED (GJ)	≤1023	
	Water use (kL)	≤2682	
	Waste impact (Tonne)	≤77.4	

Table 8.6 shows optimisation results when the constraints are set to the "average" values. The average value for all the houses with various roof assemblages and star ratings from of 3.6 and 3.9 were as follows: 71.9 tonne for GHG, 1023 GJ for CED, 2682 kL for water use and 77.4 tonne for solid waste. Interestingly, the results show that the higher star rating skillion flat roof SF3.9 is a single "best" design, which minimises all the objective functions. This outcome is the same as the multi-objective graphical approach (Section 6.3.1). This again supports the validity of the MP model.

In summary, MP modelling and graphical approaches generated similar sets of optimum designs. This supports the validity of the MP modelling approach. MP modelling identifies optimum designs but the optimum depends on whether the highest or average value constraints are applied. Applying the average constraints identified a single optimum design, the high star skillion flat roof SF3.9.

The optimisation results for floor assemblage designs are discussed in the next section.

8.2.3 MP model optimisation using SOO: floor designs

The results for MP model optimisation for the house design with various floor assemblages are summarised in Table 8.7 and Table 8.8 for constraints set to "highest" and "average" data, respectively. A sample optimisation model and results of each constraint are given in Appendix 8.G and Appendix 8.H, respectively, shown GHG objective function case only. When the constraints are set to "highest", the number of designs that are considered is 5: the case study house and all the house designs with various floor tops (4). When the constraints are set to "average", the numbers of designs considered is 3.

Table 8.7: SOO results for optimisation of floor designs - "highest" constraints

Objective function to be minimised	Target constraints: all at least as good as "highest"		"Best" design
GHG	CED (GJ)	≤1092	Mixed
	Water use (kL)	≤3281	
	Waste impact (Tonne)	≤81.1	
	LCC (AUD)	≤208656	
CED	GHG (Tonne CO_2)	≤76.2	Mixed
	Water use (kL)	≤3281	
	Waste impact (Tonne)	≤81.1	
	LCC (AUD)	≤208656	
Water Use	GHG (Tonne CO_2)	≤76.2	Mixed
	CED (GJ)	≤1092	
	Waste impact (Tonne)	≤81.1	
	LCC (AUD)	≤208656	
Solid Waste	GHG (Tonne CO_2)	≤76.2	Tiled
	CED (GJ)	≤1092	
	Water use (kL)	≤3281	
	LCC (AUD)	≤208656	
LCC	GHG (Tonne CO_2)	≤76.2	Mixed
	CED (GJ)	≤1092	
	Water use (kL)	≤3281	
	Waste impact (Tonne)	≤81.1	

Table 8.7 shows that the mixed floor design minimises all impact categories except for solid waste. The ceramic tiled floor had the minimum solid waste. Again, there is no single best design. This is slightly different to the results using a graphical approach (Section 7.3), where the mixed floor was selected as "best" for all objective functions. While there is only a negligible difference between the solid waste impact for tiled and mixed floor, so either is equally good, only the graphical approach could consider this. This reveals a weakness of the MP modelling approach: it is not

sophisticated enough to take into account if first and second best designs are so similar they are not significantly different. Only the minimum value is considered.

Table 8.8: SOO results for optimisation of floor designs-"average" constraints

Objective function to be minimised	Target constraints: all at least as good as "average"		"Best" design
GHG	CED (GJ)	≤1016	Mixed
	Water use (kL)	≤3141	
	Waste impact (Tonne)	≤81.7	
	LCC (AUD)	≤204338	
CED	GHG (Tonne CO_2)	≤71.7	Mixed
	Water use (kL)	≤3141	
	Waste impact (Tonne)	≤81.7	
	LCC (AUD)	≤204338	
Water Use	GHG (Tonne CO_2)	≤71.7	Mixed
	CED (GJ)	≤1016	
	Waste impact (Tonne)	≤81.7	
	LCC (AUD)	≤204338	
Solid Waste	GHG (Tonne CO_2)	≤71.7	Carpet
	CED (GJ)	≤1016	
	Water use (kL)	≤3141	
	LCC (AUD)	≤204338	
LCC	GHG (Tonne CO_2)	≤71.7	Mixed
	CED (GJ)	≤1016	
	Water use (kL)	≤3141	
	Waste impact (Tonne)	≤81.7	

For average constraints, the average values were calculated from the results for all of the designs. The average value for GHG was 71.7 tonne, for CED was 1016 GJ, for water use was 3141 kL, and for solid waste was 81.7 tonne. Overall, the house design with the mixed floor looks an attractive choice, as it is ranked top or in the top two for each objective function. For these constraints, the results from MP modelling and graphical approaches are similar (Section 7.3). Again, this supports the validity of MP modelling.

In summary, MP modelling and graphical approaches identified similar optimum designs or similar sets of optimum designs for wall, roof and floor assemblages. This confirms the validity of the MP modelling approach. The "best" design depends on the choice of target constraints. Using constraints based on the base case or the lowest constraint values is not useful in this study because they provided limited or no feasible solutions. Using highest values for constraints generally yielded the same results as a SOO graphical approach, with no single best design identified. Using average values for the target constraints meant a smaller range of designs was considered, each at least as good as the “average” design. Then a single best design was identified: the weatherboard house with high star rating (WB3.9), the high star rating house with skillion flat roof assemblage (SF3.9) and the house design with the mixed floor are the most attractive choices for wall, roof and floor designs respectively, as they were ranked top or in the top two designs for all objective functions. MP modelling using a MOO approach is discussed in the next section.

8.3 OPTIMISATION OF WALL, ROOF AND FLOOR ASSEMBLAGE DESIGNS USING MOO

In Section 8.2, results from MP modelling using SOO were presented: one objective function at a time was minimised for the house designs with different wall, roof or floor assemblages. In this section, MOO is undertaken for the same designs, using an MP modelling approach, minimising multiple objective functions at the same time. Such an approach can identify a single optimum solution by combining the multiple objective functions into one objective function, thereby transforming the problem to one readily solved with a SOO approach. Typically, a weighted sum approach is applied (Hawe & Sykulski 2008; Konak, Coit & Smith 2006).

In this study, the normalised objective functions are converted to a SOO problem with a scalar single composite objective function. The normalisation calculation was discussed in Section 2.6.3. There is no particular rule to select the weighting for the objective functions (Shuqing 2005). A random weight is a common approach to generate a set of solutions (Murata et al 1996; Murata et al 2001; Shuqing 2005). A range of sets of weightings was applied in this study.

8.3.1 MP model optimisation using MOO - Wall designs

The outcome from minimising a scalar single composite objective function will depend on which objective functions are included. In this section, results are presented for two composite objective functions. The first composite objective function comprises all five-impact indicators (GHG, CED, water use, solid waste and LCC), normalised with the optimum value. The second composite objective function comprises three normalised impact indicators, those that varied the most with assemblage design (GHG, CED and LCC).

Table 8.9: MOO results for optimisation of wall designs -"average" constraints

Objective function to be minimised		**Target constraints: all at least as good as "average"**		**"Best" design**
All objective functions	(.2 GHG + .2 CED + .2 WATER + .2 WASTE + .2 LCC)	GHG (Tonne CO2)	≤ 1.12	WB3.9
		CED (GJ)	≤ 1.04	
		Water use (kL)	≤ 1.01	
		Waste impact (Tonne)	≤ 1.09	
		LCC (AUD)	≤ 1.05	
3 Major objective functions	(.10 GHG + .10 CED + .80 COST)	GHG (Tonne CO2)	≤ 1.12	FC3.9
		CED (GJ)	≤ 1 .04	
		Water use (kL)	≤ 1.01	
		Waste impact (Tonne)	≤ 1.09	
		LCC (AUD)	≤ 1.05	
	(.15 GHG + .15 CED + .70 LCC)	GHG (Tonne CO2)	≤ 1.12	FC3.9
		CED (GJ)	≤ 1.04	
		Water use (kL)	≤ 1.01	
		Waste impact (Tonne)	≤ 1.09	
		LCC (AUD)	≤ 1.05	
	(.2 GHG + .2 CED + .60 LCC)	GHG (Tonne CO2)	≤ 1.12	FC3.9
		CED (GJ)	≤ 1.04	
		Water use (kL)	≤ 1.01	
		Waste impact (Tonne)	≤ 1.09	
		LCC (AUD)	≤ 1.05	
	(.25 GHG + .25 CED + .50 LCC)	GHG (Tonne CO2)	≤ 1.12	WB3.9
		CED (GJ)	≤ 1.04	
		Water use (kL)	≤ 1.01	
		Waste impact (Tonne)	≤ 1.09	
		LCC (AUD)	≤ 1.05	
	(.30 GHG + .30 CED + .40 LCC)	GHG (Tonne CO2)	≤ 1.12	WB3.9
		CED (GJ)	≤ 1.04	
		Water use (kL)	≤ 1.01	
		Waste impact (Tonne)	≤ 1.09	
		LCC (AUD)	≤ 1.05	
	(.33 GHG + .33 CED + .34 LCC)	GHG (Tonne CO2)	≤ 1.12	WB3.9
		CED (GJ)	≤ 1.04	
		Water use (kL)	≤ 1.01	
		Waste impact (Tonne)	≤ 1.09	
		LCC (AUD)	≤ 1.05	

Table 8.9 shows results for all houses designs with various wall assemblages. The constraints were set to the "average" values of the normalised objective functions. A sample optimisation model and results are given in Appendix 8.J, shown one case (all objective functions) only. When this set of constraints is used, the numbers of designs considered is 8.

Various weightings were applied, similar to the approach of Borissova & Mustakerov (2008) and Eren (2007). For the first composite objective function, a weighting of 20% was applied to each impact indicator. For the second composite objective function, various sets of weightings were applied, from 10%, 15%, 20%, and 25% to 33% for GHG and CED impacts and from 80%, 70%, 60%, and 40% to 34% for LCC (Table 8.9). In each case, the weightings must of course sum to 100%. Varying the weighting for one objective can assess whether the best design is sensitive to the weighting (Grodzevich & Romanko 2006; Khan & Ardil 2009; Konak, Coit & Smith 2006). Average and highest target constraints values were applied, as these generated the most interesting sets of optimum designs in Section 8.2.1.

The first optimisation result shown in Table 8.9 is for a composite objective function including all five-impact indicators. The MP model using MOO predicts a single "best" design: the highest rating weatherboard house design WB3.9.

The second optimisation results shown in Table 8.9 are for a composite objective function including only the three most sensitive impact indicators (GHG, CED and LCC). Various weightings were applied to the normalised values for each impact indicator, as shown. The MP model using MOO again predicts a single "best" design. However, the best design depends on the weighting. The higher star rating weatherboard clad house (WB3.9) is the "best" design, if the weighting for LCC is 50% or lower. The highest star rating fibre cement sheet clad house FC3.9 is the "best" design, if the weighting for LCC is 60% or higher. Hence, the best design depends on the relative weightings between environmental impact and cost.

The appropriate choice of the weighting for objective functions depends on the values and preferences of the stakeholders. The decision maker needs to determine the weighting for the multiple objectives. Then MP modelling with MOO is an effective approach to identify a single best design.

Table 8.10: MOO results for optimisation of wall designs -"highest" constraints

Objective function to be minimised		Target constraints: all at least as good as highest		"Best" design
All objective functions	(.2 GHG + .2 CED + .2 WATER + .2 WASTE + .2 LCC)	GHG (Tonne CO2)	≤ 1.20	WB3.9
		CED (GJ)	≤ 1 .07	
		Water use (kL)	≤ 1.01	
		Waste impact (Tonne)	≤ 1.24	
		LCC (AUD)	≤ 1.18	
3 Major objective functions	(.10 GHG + .10 CED + .80 LCC)	GHG (Tonne CO2)	≤ 1.20	FC3.7/FC3.6
		CED (GJ)	≤ 1 .07	
		Water use (kL)	≤ 1.01	
		Waste impact (Tonne)	≤ 1.24	
		LCC (AUD)	≤ 1.18	
	(.15 GHG + .15 CED + .70 LCC)	GHG (Tonne CO2)	≤ 1.20	FC3.7/FC3.6
		CED (GJ)	≤ 1 .07	
		Water use (kL)	≤ 1.01	
		Waste impact (Tonne)	≤ 1.24	
		LCC (AUD)	≤ 1.18	
	(.2 GHG + .2 CED + .60 LCC)	GHG (Tonne CO2)	≤ 1.20	WB3.9
		CED (GJ)	≤ 1 .07	
		Water use (kL)	≤ 1.01	
		Waste impact (Tonne)	≤ 1.24	
		LCC (AUD)	≤ 1.18	
	(.25 GHG + .25 CED + .50 COST)	GHG (Tonne CO2)	≤ 1.20	WB3.9
		CED (GJ)	≤ 1 .07	
		Water use (kL)	≤ 1.01	
		Waste impact (Tonne)	≤ 1.24	
		LCC (AUD)	≤ 1.18	
	(.30 GHG + .30 CED + .40 LCC)	GHG (Tonne CO2)	≤ 1.20	WB3.9
		CED (GJ)	≤ 1 .07	
		Water use (kL) Waste impact (Tonne)	≤ 1.01 ≤ 1.24	
		LCC (AUD)	≤ 1.18	
	(.33 GHG + .33 CED + .34 LCC)	GHG (Tonne CO2)	≤ 1.20	WB3.9
		CED (GJ)	≤ 1 .07	
		Water use (kL)	≤ 1.01	
		Waste impact (Tonne)	≤ 1.24	
		LCC (AUD)	≤ 1.18	

Table 8.10 shows results for all house designs with various wall assemblages. A sample optimisation model and results are given in Appendix 8.J, shown one case (all objective function) only. The constraints were set to the "highest" values of the normalised objective functions.

The results show that again the model predicts a single best design that depends on the composite objective function and the weighting. Again, the highest star rating weatherboard clad house design WB3.9 is the best design when a composite objective function including all five impacts indicators is minimised, subject to an equal weighting (20%).

The highest star rating weatherboard clad house design WB3.9 is also the best design when a composite objective function including the three most sensitive impact indicators is minimised, subject to a weighting of 60% or less on LCC. The lower star rating FC sheet clad house designs (FC3.6/FC3.7) are the "best" designs, if the weighting for LCC is 70% or higher. Hence, the best design again depends on the relative weightings between environmental impact and cost.

The best design also depends on the constraints applied in the model. WB3.9 is predicted to be the best design when both "average" and "highest" constraints are applied in combination with a weighting of 50% or less on LCC. However, with a weighting more than 50% for LCC, the best design is either FC3.9 or FC3.6/FC3.7, depending on the constraints applied. While use of highest constraints considers all the house designs, use of average constraints excludes FC3.6/FC3.7 from consideration, as they have higher than average GHG emissions. Using the average constraints limits the designs to those with all objective functions better than average: this is a preferred set of designs from the point of view of avoiding a design with poor performance on any objective function. The results show that the MP model using MOO is a robust optimisation model.

In the next section, the MP model using MOO for the houses of roof and floor designs are illustrated using "average" target constraints only.

8.3.2 MP model optimisation using MOO - Roof designs

Table 8.11: MOO results for optimisation of roof designs -“average” constraints

Objective function to be minimised		Target constraints: all at least as good as average		“Best” design
All objective functions	(.2 GHG + .2 CED + .2 WATER + .2 WASTE + .2 LCC)	GHG (Tonne CO2)	≤ 1.05	1 SF3.9 2 MR3.8
		CED (GJ)	≤ 1.05	
		Water use (kL)	≤ 1.09	
		Waste impact (Tonne)	≤ 1.03	
		LCC (AUD)	≤ 1.01	
3 Major objective functions	(.10 GHG + .10 CED + .80 LCC)	GHG (Tonne CO2)	≤ 1.05	1. SF3.9 2. TF3.8
		CED (GJ)	≤ 1.05	
		Water use (kL)	≤ 1.05	
		Waste impact (Tonne)	≤ 1.03	
		LCC (AUD)	≤ 1.01	
	(.15 GHG + .15 CED + .70 LCC)	GHG (Tonne CO2)	≤ 1.05	1. SF3.9 2. TF3.9
		CED (GJ)	≤ 1.05	
		Water use (kL)	≤ 1.09	
		Waste impact (Tonne)	≤ 1.03	
		LCC (AUD)	≤ 1.01	
	(.2 GHG + .2 CED + .60 LCC)	GHG (Tonne CO2)	≤ 1.05	1. SF3.9 2. TF3.9
		CED (GJ)	≤ 1.05	
		Water use (kL)	≤ 1.09	
		Waste impact (Tonne)	≤ 1.03	
		LCC (AUD)	≤ 1.01	
	(.25 GHG + .25 CED + .50 LCC)	GHG (Tonne CO2)	≤ 1.05	1 SF3.9 2 TF3.9
		CED (GJ)	≤ 1.05	
		Water use (kL)	≤ 1.09	
		Waste impact (Tonne)	≤ 1.03	
		LCC (AUD)	≤ 1.01	
	(.30 GHG + .30 CED + .40 LCC)	GHG (Tonne CO2)	≤ 1.05	1 SF3.9 2 MR3.8
		CED (GJ)	≤ 1.05	
		Water use (kL)	≤ 1.09	
		Waste impact (Tonne)	≤ 1.03	
		LCC (AUD)	≤ 1.01	
	(.33 GHG + .33 CED + .34 LCC)	GHG (Tonne CO2)	≤ 1.05	1 SF3.9 2 MR3.8
		CED (GJ)	≤ 1.05	
		Water use (kL)	≤ 1.09	
		Waste impact (Tonne)	≤ 1.03	
		LCC (AUD)	≤ 1.01	

Table 8.11 shows results for all houses designs with various roof assemblages. A sample optimisation model and results are given in Appendix 8.K, shown one case only. When this set of constraints is used, the number of designs considered is 4. The results show that the model predicts a single best design that is independent of composite objective function and weighting. The higher star rating skillion flat roof house design (SF3.9) is the best design.

8.3.3 MP model optimisation using MOO - Floor designs

Table 8.12: MOO results for optimisation of floor designs -“average” constraints

Objective function to be minimised		Target constraints: all at least as good as average		“Best” design
All objective functions	(.2 GHG + .2 CED + .2 WATER + .2 WASTE + .2 LCC)	GHG (Tonne CO2)	≤ 1.08	1 MFH 2 CTH
		CED (GJ)	≤ 1.05	
		Water use (kL)	≤ 1.04	
		Waste impact (Tonne)	≤ 1.03	
		LCC (AUD)	≤ 1.06	
3 Major objective functions	(.10 GHG + .10 CED + .80 LCC)	GHG (Tonne CO2)	≤ 1.08	1. MFH 2. CTH
		CED (GJ)	≤ 1.05	
		Water use (kL)	≤ 1.04	
		Waste impact (Tonne)	≤ 1.03	
		LCC (AUD)	≤ 1.06	
	(.15 GHG + .15 CED + .70 LCC)	GHG (Tonne CO2)	≤ 1.08	1. MFH 2. CTH
		CED (GJ)	≤ 1.05	
		Water use (kL)	≤ 1.04	
		Waste impact (Tonne)	≤ 1.03	
		LCC (AUD)	≤ 1.06	
	(.2 GHG + .2 CED + .60 LCC)	GHG (Tonne CO2)	≤ 1.08	1. MFH 2. CTH
		CED (GJ)	≤ 1.05	
		Water use (kL)	≤ 1.04	
		Waste impact (Tonne)	≤ 1.03	
		LCC (AUD)	≤ 1.06	
	(.25 GHG + .25 CED + .50 LCC)	GHG (Tonne CO2)	≤ 1.08	1 MFH 2 CTH
		CED (GJ)	≤ 1.05	
		Water use (kL)	≤ 1.04	
		Waste impact (Tonne)	≤ 1.03	
		LCC (AUD)	≤ 1.06	
	(.30 GHG + .30 CED + .40 LCC)	GHG (Tonne CO2)	≤ 1.08	1 MFH 2 CTH
		CED (GJ)	≤ 1.05	
		Water use (kL) Waste impact (Tonne)	≤ 1.04 ≤ 1.03	
		LCC (AUD)	≤ 1.06	
	(.33 GHG + .33 CED + .34 LCC)	GHG (Tonne CO2)	≤ 1.08	1 MFH 2 CTH
		CED (GJ)	≤ 1.05	
		Water use (kL)	≤ 1.04	
		Waste impact (Tonne)	≤ 1.03	
		LCC (AUD)	≤ 1.06	

Table 8.12 shows results for all houses designs with various floor assemblages. A sample optimisation model and results are given in Appendix 8.L, shown one objective function only. When this set of constraints is used, the numbers of designs considered is 3. The results show that the model predicts a single best design that is independent of composite objective function and weightings. The highest star rating mixed floor house design (MFH) is the best design.

In summary, a best design is predicted by minimising multiple objectives functions using MP modelling with a MOO approach. This approach is useful to identify single solutions. In some cases, the choice of composite objective function and/or weighting may influence the outcome. A trade-off relationship can provide a set of alternative best designs, where the decision maker can select the optimal solution depending on their values and preferences for impact indicators and weightings. Hence, the decision maker can choose quantitative criteria to apply to a set of optimal solutions that reduces the set to a single optimum.

8.4 COMPARISON OF CASE STUDY AND OPTIMAL HOUSE DESIGNS

In the following section, the results are presented for three optimal house designs that are modified with selected optimal wall, roof and floor assemblages. The LCA and LCC results for these optimum house designs are compared with those of the base case house. Then, optimisation results are presented for the three optimal house designs and the base case house. For each figure in this section, the three optimum house designs are abbreviated as follows: OP1, OP2 and OP3.

8.4.1 Results for optimal and case study house designs

A selection of the most attractive choices for wall, roof and floor assemblages designs identified in Section 8.3 were put together into a whole house designs, OP1, OP2 and OP3. OP1 has best assemblage designs identified by a graphical SOO approach: the timber (TFH) floor, the highest star rating weatherboard (WB3.9) wall and the higher star rating gable tile (TF3.9) roof design. OP2 has the best assemblage designs identified by MP modelling with MOO, that is, the mixed (MFH) floor, WB3.9 wall and higher star rating skillion flat (SF3.9) roof design. The OP3 house has the mixed (MFH) floor, the highest star rating fibre cement sheet (FC3.9) wall and the higher star rating skillion flat (SF3.9) roof designs. FC3.9 was the best design for several categories identified by MP modelling with SOO. The other structural elements are the same in each design, based on the case study house design. The detailed specifications of OP1, OP2 and OP3 are given in Appendix 8.M. All the house designs are compared based on star rating, and environmental and economic impacts, as in Chapters 5 to 7.

Table 8.13: Life cycle results for optimal and base case designs

House Name (floor/wall/roof)	Star Rating	LCA impact category indicators				LCC
		GHG (Tonne)	CED (GJ)	Water (kL)	Waste (Tonne)	Cost ($)
Base Case	3.6	76.2	1080	3100	80.8	209,000
OP1 (TFH /WB3.9/TF3.9)	4.6	64.0	990	3550	79.1	214,000
OP2 (Mixed/WB 3.9/SF3.9)	4.9	63.2	960	2480	73.2	209,000
OP3 (Mixed/FC 3.9/SF3.9)	4.8	64.8	980	2500	74.6	207,000
Average	-	67.1	1000	2910	77.0	209750
Best to worst (%)	-	21	12	43	10	3
Change per star rating (%)	-	16	9.2	33	7.7	2.3

Table 8.13 shows results for the optimal house designs and includes results for the case study house (base case) to show the degree of improvement. Compared with the base case, the incremental improvements in floor, wall and roof assemblage designs increased the star rating significantly, by 1.3 stars. The optimal house designs also have much lower GHG, CED, water use and solid waste, with reductions from 10 to 43%. Only LCC has a much smaller range ($7000, or 3% of total costs), with a slight increase for one design (OP1). OP2 is the best design in terms of LCA impact category indicators, whilst OP3 has similar low values for LCA impact category indicators, and it's the best for LCC.

The effects on different environmental impact categories are comparable to several Australian studies. The rate of decrease of GHG emissions ranged from 20-30% (DSE 2007) to 9-17% per star rating (Carre 2011), similar to this study (16%). The rate of decrease of CED was up to 18% per star rating for a heritage listed building (Iyer-Raniga & Wong 2012) higher than this study (9%), which may be attributed to differences in study assumptions.

Very few studies reported water usages that are comparable: Iyer-Raniga & Wong (2012) reported that star rating had no significant effect on water usage, when compare of their two heritage buildings. No Australian studies have reported on the effect of star rating on solid waste, so the results of this study cannot be compared to another.

The cost of star rating improvements is also comparable to other Australian studies. McLeod & Fay (2011) and Belusko & O'Leary (2010) reported that an additional 1-2% cost might be required for improving a house design from 4 to 5 star rating, similar to the results for OP1. Similarly, Moore & Morrissey (2010) reported that around $4200 is required to improve the house star rating from 6 stars to 7 stars.

The detailed breakdown of results for LCA categories and LCC for each life cycle stage are shown in Table 8.14.

Table 8.14: Life cycle stages results for optimal and base case designs

Indicators	House Name	Construction	Operation	Maintenance	Disposal
GHG (Tonne)	OP1	28.3	36.4	5.00	-5.64
	OP2	28.6	34.2	4.71	-4.37
	OP3	29.5	34.2	5.64	-4.60
	Base Case	26.0	48.0	6.43	-4.21
	Best to worse %	**13.8**	**40.3**	**36.6**	**34.0**
CED (GJ)	OP1	438	419	118	14.1
	OP2	442	393	114	13.9
	OP3	451	394	123	14.0
	Base Case	378	560	127	13.0
	Best to worse %	**19.2**	**42.5**	**10.8**	**8.93**
Water (kL)	OP1	2420	48	1070	-0.39
	OP2	1360	48	1075	-0.39
	OP3	1360	48	1075	-0.39
	Base Case	1940	65	1090	-0.29
	Best to worse %	**78.2**	**36.1**	**1.75**	**35.1**
Solid Waste (Tonne)	OP1	3.89	1.26	3.63	70.3
	OP2	3.95	1.20	3.45	64.6
	OP3	3.96	1.19	3.46	66.0
	Base Case	4.95	1.63	3.86	70.3
	Best to worse %	**27.4**	**37.0**	**11.9**	**8.9**
LCC ($)	OP1	138,000	15,200	55,000	5,800
	OP2	134,000	14,200	54,500	6,620
	OP3	132,000	14,300	53,900	6,660
	Base case	129,000	20,300	53,900	5,620
	Best to worse %	**7.27**	**43.0**	**2.03**	**18.5**

Table 8.14 shows that the GHG and CED indicators for the optimal designs generally increase in construction and decrease in the operation life phase compared to the base case house. For the category of GHG, the emissions in each life cycle phase vary significantly from best to worst. The results for CED also vary significantly for the construction and operation phases. Both the GHG and CED emissions in the operation phase show a very significant reduction compared to the base case house (by around 40%). This correlates with the star rating as expected, which increases from 3.6 for the base case to 4.9 stars for OP2. The star rating reflects the amount of heating and cooling energy required for average occupancy.

The water use and solid waste show similar changes, with largest impact variation also occurring in the construction and operation phases. As discussed in Chapter 5, there are small but not significant differences in water usage and solid waste during the operation life phase. This is due to differences in energy usage, as the life cycle inventory for energy production includes water usage and solid waste

Table 8.14 shows that LCC for the optimal designs varies significantly in the operation and disposal phases compared to the base case house. Most of the life cycle cost occurs during the construction phase. The higher costs associated with optimal designs (up to $9000) was offset by savings in the operation phase (up to $6100). The construction cost goes up due to the use of additional materials or more expensive construction techniques to achieve higher star rating. Total life cycle cost shows a small increase or decrease depending on which material or construction techniques are used to achieve the higher star rating.

Overall, the optimisation of the assemblage designs achieves very significant reductions in environmental impacts at a similar life cycle cost. Optimisation results are presented in the next section.

8.4.2 MP model optimisation using MOO – whole house designs

Table 8.15 and Table 8.16 show results from MP modelling with MOO using 'average' and 'highest' target constraints, respectively, for the optimal and base case designs.

Table 8.15: MOO results for optimal and case study designs - "average" constraints

Objective function to be minimised		**Target constraints: all at least as good as "Average"**		**"Best" design**
All objective functions	(.2 GHG + .2 CED + .2 WATER + .2 WASTE + .2 LCC)	GHG (Tonne CO2)	≤ 1.062	OP2
		CED (GJ)	≤ 1.042	
		Water use (kL)	≤ 1.173	
		Waste impact (Tonne)	≤ 1.051	
		LCC (AUD)	≤ 1.013	
3 Major objective functions	(.33 GHG + .33 CED + .34 LCC)	GHG (Tonne CO2)	≤ 1.062	OP2
		CED (GJ)	≤ 1.042	
		Water use (kL)	≤ 1.173	
		Waste impact (Tonne)	≤ 1.051	
		LCC (AUD)	≤ 1.013	
3 Major objective functions	(.13 GHG + .13 CED + .74 LCC)	GHG (Tonne CO2)	≤ 1.062	OP3
		CED (GJ)	≤ 1.042	
		Water use (kL)	≤ 1.173	
		Waste impact (Tonne)	≤ 1.051	
		LCC (AUD)	≤ 1.013	

When the set of highest constraints is used, the number of designs that are considered is 4: the optimal house designs (3) and the case study house. When the set of average constraints is used, the numbers of designs considered is limited to 2 (OP2 and OP3), as these two designs are the only ones with all values lower than the category average.

As in Section 8.3.1, two composite objective functions are calculated, one with five-impact indicators and one with the three impact indicators that varied the most with assemblage design. Selected weightings are used, reflecting different stakeholder preferences. If all objective functions are equally weighted, the single best design is the highest star rating optimal design OP2. If the three major objective functions are minimised, then OP3 is the best design when the weighting for LCC is 0.74 or greater. The reason for this is that the OP2 design has lower life cycle environmental impacts than OP3, while OP3 has slightly lower LCC.

Table 8.16: MOO results for optimal and case study house designs -"highest" constraints

Objective function to be minimised		Target constraints: all at least as good as "Highest"		"Best" design
All objective functions	(.2 GHG + .2 CED + .2 WATER + .2 WASTE + .2 LCC)	GHG (Tonne CO2)	≤ 1.21	OP2
		CED (GJ)	≤ 1.12	
		Water use (kL)	≤ 1.12	
		Waste impact (Tonne)	≤ 1.10	
		LCC (AUD)	≤ 1.03	
3 Major objective functions	(.33 GHG + .33 CED + .34 LCC)	GHG (Tonne CO2)	≤ 1.21	OP2
		CED (GJ)	≤ 1.12	
		Water use (kL)	≤ 1.12	
		Waste impact (Tonne)	≤ 1.10	
		LCC (AUD)	≤ 1.03	
3 Major objective functions	(.13 GHG + .13 CED + .74 LCC)	GHG (Tonne CO2)	≤ 1.21	OP3
		CED (GJ)	≤ 1.12	
		Water use (kL)	≤ 1.12	
		Waste impact (Tonne)	≤ 1.10	
		LCC (AUD)	≤ 1.03	

Table 8.16 shows the results if the highest constraints are used. This predicts the same best design as when average constraints are used, for the same weightings. Again, as OP2 has lower life cycle environmental impacts than OP3, it is the superior design when higher weighting is given to environmental impacts, while OP3 has slightly lower LCC, so it is superior when a higher weighting is given to cost. It has the

same tipping point (a weighting of 0.74 to LCC) because the two best designs are the same with both average and highest constraint.

8.4.3 Discussion

In the building industry today, it is common for stakeholders to select the best house design after considering a limited set of variables, such as star rating and construction costs. The preferred design is selected by optimising two variables. If an MP modelling with MOO approach is used, the best design can be selected by optimising a wide range of objective functions subject to a set of constraints (Zacharia 2003). The objective functions and weightings can also be selected by the stakeholders to reflect their values and preferences. The range of indicators can be evaluated across the whole building life cycle, allocating impacts in each life stage, and allowance made for discounted future costs. The decision maker can choose the quantitative criteria to generate a set of optimal solutions. A different best solution or set of best solutions will be found depending on many factors including the model assumptions, range of environmental and economic indicators considered, and the chosen constraints and weightings. For example, the higher weighting percentage of LCC (74%) influences the outcomes for OP3, if the three major objective functions are minimised. This is attributed that the OP3 design has lower LCC than OP2.

In the case study residential building in Brisbane, two best designs were identified that reduced the environmental impacts significantly across a range of category indicators, at approximately the same life cycle cost. The choice of impact categories and weighting influenced the outcome. There are no similar studies, which used mathematical optimisation with an LCC and LCA approach to Australian buildings. Hence, this study provides a novel contribution on the application of multi-criteria decision making to optimisation of residential building design.

The results show that MP modelling with a MOO approach yields different results to a two variable optimisation approach. Hence, it is a useful approach to determine best set of designs, taking into account stakeholder's preferences across a wide range of environmental and economic impact categories.

8.5 SUMMARY

In summary, the “best” design or set of designs can be found using an MP model with MOO that reduces multiple objectives to a single composite objective function, subject to target constraints. The preferences of the decision maker are incorporated in choice of objective functions and weightings. Using average constraints offered the best range of designs for optimisation in this case study. The “best” design then has the lowest or lower than average values across a range of indicators.

There are two best designs for the case study house. One has a star rating of 4.9, a mixed (tile/timber) floor, an insulated weatherboard wall, an insulated skillion flat roof, and a total cost of $209 000. The second has the same assemblages except it has a fibre cement cladding, a star rating of 4.8, and a total cost of $207000.

In the next Chapter 9, conclusions are drawn with respect to the research questions. The main contributions and suggestions for further research are outlined.

CHAPTER 9: CONCLUSIONS AND FURTHER RESEARCH

Conclusions; Further research and Limitations

9.1 CONCLUSIONS

Aim

As discussed in Chapter 1, the aims of the research undertaken here were:

1) to evaluate the effect on the whole life cycle of a residential building of varying envelope materials and construction techniques, considering both economic and environmental impacts, and

2) to provide a useful optimisation framework to evaluate these effects.

Approach

Various modelling practices are associated with LCA, LCC and optimisation on buildings. Standard methodology can be used for star rating assessment, LCA and LCC, and ideally, a regional LCI database and regional economic factors are used. A standard methodology can integrate commonly used materials, design and building techniques to calculate the star rating, LCA, LCC and optimisation for a house over its whole lifetime. *AccuRate* is a suitable program to evaluate the star rating as it includes a database of assemblages commonly used in the Australian residential building industry. *SimaPro* is a suitable program to undertake a streamlined LCA to evaluate the life cycle environmental impacts, using the Australian database AusLCI. *Excel* can be used to model LCC combined with a suitable reference for the Australian building industry such as Rawlinson's. A graphical optimisation approach can be taken using *Excel,* and mathematical programming optimisation can be undertaken using *LINDO* to identify the best or set of best designs using a trade-off relationship from the choice of decision maker. *AccuRate*, *SimaPro* and *LINDO* are useful tools that are readily available, easy to use and adequate for the purpose.

A case study approach is a useful way to evaluate effectiveness of tools and techniques in LCA and LCC studies.

Findings

In broad terms, the LCA impact indicators for a residential house are dominated by different life cycle stages. The construction and operation life stages dominate the total impacts for GHG (97%) and CED (87%). For water use, the construction and maintenance life stages dominate the total impacts (98%). For solid waste, the disposal life phase dominates the total impact (87%). The construction and maintenance life stages dominate LCC (88%). The construction costs for a two-storey three-bedroom semi-detached house built in Brisbane are quite low, around $130,000. The results for the case study house show trends similar to several previous studies of residential house designs, confirming the usefulness of taking a case study approach and the accuracy of this particular model. The results for the case study house show good agreement with the results for a recent study of a similar modern Australian house in a similar climate, with similar assemblages, the same lifetime and similar boundary exclusions. Other studies did not show good agreement, attributed to differences in design, lifetime, region, exclusions and assumptions.

Sensitivity analysis shows that results for the case study house for two LCA impact categories (GHG and CED) are sensitive to lifespan and transport distance, while water usage is sensitive to maintenance schedules. The LCC models are sensitive to the discount rate, as it affects the future costs. This means that the assumptions are the key drivers determining the comparability of LCA and LCC studies of residential houses.

Research Questions

This research answers two main research questions. The first research question was: *What is the effect on the whole life cycle environmental and economic impact of a residential building of varying materials in the wall, roof and floor assemblage designs?* To answer this research questions, this study analysed 18 wall, 8 roof and 4 floor alternative designs to identify optimal wall, roof and floor assemblages.

Changing wall, roof and floor assemblages has a significant effect on the environmental and cost impacts of a residential house. In particular, GHG, solid waste and LCC are significantly affected by wall assemblage design, GHG and CED are significantly affected by floor design, and water use is affected by roof assemblage design. The house designs with higher star ratings have lower GHG emissions and CED and higher LCC.

For house designs with modified wall assemblages, overall, the best design depends on the cladding type. In terms of materials, the house design with pine saw log cladding has the lowest GHG emissions and CED and water usage; weatherboard has the lowest solid waste and LCC.

The optimum roof assemblage depends on the impact indicators and star rating. For global impact categories, the better designs are gable tile and skillion flat. For regional impact categories, the optimum set is different: skillion flat and skillion pitch. Overall, the high star rating design with a skillion flat roof is an attractive trade-off.

The optimum floor assemblage depends on the impact category and the life cycle phase. Floor design significantly affects GHG and CED emissions overall, water use in the maintenance life phase only. Star rating significantly affects LCC in the operation, maintenance and disposal life phases. The best design was consistently the mixed floor tops, and the worst, carpet.

Remarkable reductions in LCA and LCC impacts are seen when incremental design improvements for wall, roof and floor are combined in one building design. When optimal wall (weatherboard), roof (skillion flat) and floor (mixed) assemblages are used together as one optimal design, the improvements are much more pronounced than when only one element is modified. The environmental impacts reduce by 10 to 43%, compared to the base case house. The cost is similar, or slightly reduced: savings in operations and maintenance offset the higher construction costs.

The second research question was: *Which optimisation approach is the most useful for comparing these effects?* To answer this research question, this study used a graphical approach as well as Mathematical Programming (MP) modelling to identify the “best” designs. Similar outcomes are found using a graphical approach and MP modelling using single objective optimisation (SOO) with highest constraints: both have the same weakness that neither identifies a single best design. The best design depends on material, star rating and choice of objective functions and constraints.

MP modelling with a multi objective optimisation (MOO) approach minimises multiple objectives functions at the same time: these are combined to a single scalar composite function using normalisation and weighting. MP modelling using MOO predicts a single best design for a wide variety of designs. Hence, it is the most useful approach to identify the optimum assemblages. The selected impact categories, constraints and weightings form a set of criteria that influence the optimum design. These criteria can be chosen to reflect the preferences of the stakeholder or decision maker. The optimum design is then tailored to the needs of the stakeholder.

Novel contribution

The novel contribution of this research is as follows:

- Development of a detailed LCA and LCC model of a case study house. Creation of multiple house designs with different building envelopes assemblages. Identification of optimised floor, wall and roof assemblages among 31 designs. Creation of multiple house designs using optimised assemblages. Identification of the optimal house design with vastly reduced impacts on the environment at the same cost among 3 optimal designs.

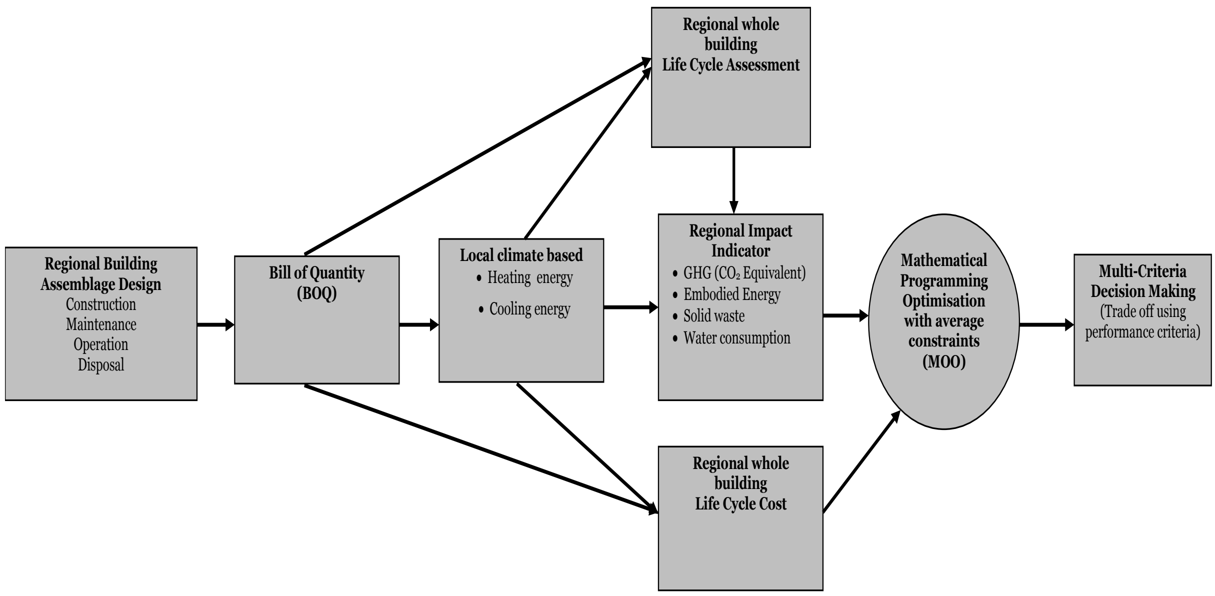
- Examination of effect of incremental improvements in assemblage design on life cycle environmental and cost impacts across a building's life cycle stages. Assessment of significance of those effects when star rating is increased.

- Development of an optimisation framework for design of residential buildings that considers a comprehensive set of environmental and cost impacts; this framework can be applied in different regions by use of local building design, costs, climate and LCI data.

- Application of different optimisation approaches to selection of best house designs, including constrained and unconstrained single and multi objective optimisation approaches, graphical approach and mathematical programming modelling. Selection of the best approach to identify a single best design as MP modelling with MOO, using average constraints. Identifying functional constraints and performance criteria that can help house designers to make decisions more effectively.

The figure below captures the novel aspects of the research findings in the optimisation framework. The original framework presented in Chapter 3 has been modified to include the key new elements: "comprehensive", "regions", "local building design", "climate", "MP modelling" and "performance criteria".

Figure 9.1: Optimisation framework for Multi-criteria decision-making



9.2 FURTHER RESEARCH

The suggested further research is as follows.

- The outcomes of this study were influenced by the interaction of building typology, construction techniques, and geographical location. Further work could be undertaken to develop a number of reference case studies. These could be used by builders and architects to make more informed design decisions. Similarly, they could be used to develop building policy and guidelines, and set benchmarks for residential buildings.

- Other multi-objective optimisation techniques could be used to test the robustness of the model and method.

- Multi criteria decision-making techniques could be applied with MP modelling using MOO to assess whether better design alternatives could be identified from the trade-off table.

- This optimisation framework could be developed further for optimisation of design of commercial buildings.

- The approach could be applied to different case studies in different climates to assess the usefulness of the approach in different regions of Australia using different building techniques, materials and assemblages. In particular, it is of interest if the outcomes are similar at a higher star rating range such as 6 stars. To reach 6 stars, further modifications to elements would be required, such as window glazing, ceiling fans, shading, ventilation, and sealing.

- This research has identified a useful optimisation framework. However, for it to become widely used in the building industry, it needs to be converted into a tool that has wider applicability and is easier to apply and generate results more quickly. Therefore, further work is required to reduce the complexity of a number of methodological issues.

There were a number of limitations of the current study, and duration of the study did not allow pursuit of a number of areas of interest. These will be outlined in the next section.

9.3 LIMITATIONS

This study used a Brisbane 3.6 star rating residential house design as a case study. Owing to the regional nature of LCA data, the results from this study are not directly comparable to other regions, although trends are expected to be similar. A design with such a low star rating can no longer be built under the Australian Building Code: new house designs must have a star rating of at least 6 stars. The best assemblages and the best optimisation approach may be different for houses with higher star rating, so this limits the applicability of the result. As house design has significant regional variation, the study outcomes may not be relevant for different house designs using different materials and assemblages popular in other regions of Australia.

REFERENCES

ABCB (Australian Building Codes Board) 2006, *Protocol for House Energy Rating Software*, ABCB, Canberra.

ABCB (Australian Building Codes Board) 2010, *Applying energy efficiency provisions to new buildings work associated with existing Class 2 to 9 buildings*, ABCB, Canberra.

ABS (Australian Bureau of Statistics) 2001, *The Australian housing stock: 1911 and 1996 Housing: Australian Social Trends, ABS Cat.4102.0*, ABS, Canberra.

ABS (Australian Bureau of Statistics) 2004, *Household and Family Projections,* cat. no. 3236.0, ABS, Canberra.

ABS (Australia Bureau of Statistics) 2010, *Year Book Australia, 2009–10*, ABS, Canberra, viewed on 30th March 2012, <www.abs.gov.au>.

ABS (Australia Bureau of Statistics) 2012, *Year Book Australia, 2012: Housing*, ABS, Canberra, viewed on 30th May 2013, <www.abs.gov.au>.

Adalberth, K, Almgren, A & Petersen, E 2001, 'Life Cycle Assessment of four Multi-Family Buildings', *International Journal of Low Energy and Sustainable Buildings*, vol. 2, pp. 1-21.

Alarcon-Rodriguez A, Ault G & Galloway, S 2010, 'Multi-objective planning of distributed energy resources: a review of the state-of-the-art', *Renewable and Sustainable Energy Reviews*, vol. 14, pp. 1553-1366.

Alegría, LRP & Calderón, CV 2006, 'A multi-objective programming approach for optimal management of the Río Caonillas watershed in north-central Puerto Rico', *in Proceedings of Fourth LACCEI International Latin American and Caribbean Conference for Engineering and Technology (LACCET'2006)*, 21-23 June 2006, Mayagüez, Puerto Rico.

Ardente, F, Beccali, M, Cellura, M & Mistretta, M 2008, 'Building energy performance: A LCA case study of kenaf-fibres insulation board', *Energy and Buildings*, vol. 40, pp. 1–10.

Arnold, P 2011, 'The Scientific Approach to Building Simulations: The New Zealand Context', *in Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association*, Sydney, 14-16 November.

ARUP 2006, *Consultancy Study on Life Cycle Energy Analysis of Building Construction*, Ove Arup & Partners Hong Kong Ltd, Electrical and Mechanical Services Department, Consultancy Agreement no. CAO L013, Hong Kong.

Asadi, E, Gameiro da Silva, M, Antunesc, CH and Dias, L 2012, 'Multi-objective optimization for building retrofit strategies: A model and an application', *Energy and Buildings*, vol. 44, pp. 81–87.

ASBEC (Australian Sustainable Built Environment Council) 2008, *Building A Low Carbon Economy With Energy Efficient Buildings*, ASBEC, Australia.

Ashby, M 2000, 'Multi-Objective Optimisation in Material Design and Selection', *Acta Materialia*, vol. 48, no. 1-1, pp. 359-369.

ASTM (American Society for Testing Materials) 2002, *Standard Practice for measuring Life-Cycle Costs of Buildings and Building Systems E 917-02*, ASTM, Philadelphia.

AusLCI 2009, 'Australian Life Cycle Inventory', viewed on 12th November 2009, <www.auslci.com.au>

Azapagic, A & Clift, R 1999, 'Life cycle assessment and multi-objective optimisation' *Journal of Cleaner Production*, vol. 7, pp. 135–143.

Bajpai, A, Ekane, N, Wang, X, & Liu, X 2008, 'A Comparative Life Cycle Assessment of a Wooden House and a Brick House', viewed on 16th November 2009 <www.infra.kth.se/fms/utbildning/lca/project%20reports/Group%206%20-%20House.pdf>.

Bakis, N, Kagiouglou, M, Aouad, G, Amaratunga, D, Kishk, M & Al-Hajj, A 2003, ‘An Integrated Environment for Life Cycle Costing in Construction’, Viewed on 3rd August 2011 <citeseerx.ist.psu.edu>

Ballinger, JA 1988, ‘The 5 star design rating system for thermally efficient, comfortable housing in Australia’, *Energy and Buildings*, vol.11, no. 1/3, pp. 65-72.

BCA (Building Code of Australia) 2005, *Class 1 and Class 10 Buildings, Housing Provisions, Volume Two. Energy Efficiency*, BCA, Australian Building Codes Board, Canberra.

Bejrum, H, Lundstrom, S & Soderber, B 1986, *The economic of real estates in longterm perspective, analysis of empirical data*, Report 5:23, Royal Institute of Technology, Stockholm, Sweden.

Belusko, M & O’Leary, T 2010, ‘Cost analyses of measures to improve residential energy ratings to 6 stars-playford North Development, South Australia’, *Australasian Journal of Construction Economics and Building*, vol. 10, no. ½, pp. 36-47.

Bilec, MM 2007, 'A hybrid life cycle assessment model for construction processes', Ph.D. Thesis, University of Pittsburgh, United State of America.

Blanchard, S & Reppe, P 1998, *Life Cycle Analysis of a Residential Home in Michigan*, University of Michigan, School of Natural Resources and Environment, Michigan.

Blengini, G 2009, 'Life cycle of buildings, demolition and recycling potential: A case study in Turin, Italy', *Building and Environment*, vol. 44, pp. 319–330.

Borissova, D□ & Mustakerov, I 2008, ‘Multicriteria Choice of Night Vision Devices Considering the Impact of Their Performance Parameters’ *Advanced Modelling and Optimization*, vol 10, no 1.

Bowyer J, Briggs D, Lippke B, Perez-Garcia J & Wilson J 2005, *Life Cycle Environmental Performance of Renewable Building Materials in the Context of Residential Construction*, Consortium for Research on Renewable Industrial Materials (CORRIM), phase I research report, Consortium for Research on Renewable Industrial Materials (CORRIM, Inc.).

Building Commission 2011, ‘What you need to know about 6 Star’, Building Commission, Australia

Carre, A 2011, *A Comparative Life Cycle Assessment of Alternative Constructions of a Typical Australian House Design*, Forest & Wood Products Australia Limited, Melbourne.

Castro-Lacouture, D, Sefair, JA, Flórez, L & Medaglia, AL 2009, ‘Optimization model for the selection of materials using a LEED-based green building rating system in Colombia,’ *Building and Environment,* vol. 44, no. 6, pp. 1162-1170.

Chen, D, Syme, M, Seo, S, Chan, WY, Zhou, M & Meddings, S 2010, *Development of an Embodied CO2 Emissions Module for AccuRate*, Forest & Wood Products Australia Limited, Melbourne.

Commonwealth of Australia 2010, *Your Home Technical Manual*, fourth Edition, Department of Climate Change and Energy Efficiency, Australian government, Canberra.

Crawford, RH 2011, Life Cycle Water Analysis of an Australian Residential Building And Its Occupants, *in the Proceedings of 7th Australian Life Cycle Assessment Conference, 9-10th March 2011,* Melbourne.

Crawford, RH & Pullen, S 2011, ‘Life cycle water analysis of a residential building and its occupants’ *Building Research & Information*, vol. 39, no. 6, pp. 589-602.

Crawford, RH, Czerniakowski, I & Fuller, RJ 2011, ‘Optimising the life cycle energy performance of residential buildings’, *in the proceedings of 45th Annual Conference of the Architectural Science Association*, The University of Sydney, Sydney.

Cuellar-Franca, RM & Azapagic, A 2012, ‘Environmental impacts of the UK residential sector: Life cycle assessment of houses’, *Building and Environment,* vol. 54, pp. 86-99.

CWC 2004, *Energy and the Environment in Residential Construction*, Sustainable Building series, no. 1, Canadian Wood Council, Ontario, Canada, viewed on 16th July 2008, <www.cwc.ca>.

Davis, M & Horvei, T 1995, *Handbook for economic analysis of energy projects*, Midrand: Development Bank of Southern Africa.

DEH (Department of the Environment and Heritage) 2006, *Scoping Study to Investigate Measures for Improving the Environmental Sustainability of Building Materials*, Australian Greenhouse Office, Canberra.

Delsante A 2004, *A Validation of the "AccuRate" Simulation Engine Using BESTEST*, CSIRO, Canberra.

Delsante A 2007, *A comparison of NatHers, FirstRate and AccuRate predications of the differences between slab-on-ground floors and suspended timber floors*, Forest & Wood Products Australia Limited, Melbourne.

Department of Infrastructure 2005, *Guideline on economic, social and environmental cost-benefit analysis*, Melbourne, Victoria.

DEWHA (Department of the Environment, Water, Heritage and the Arts) 2008, *Energy Use in the Australian Residential Sector 1986-2020*, DEWHA, Canberra.

Dewsbury, M, Soriano, F, Nolan, G & Fay, R 2009, *Comparison of Test Cell Thermal Performance & The Empirical Validation of AccuRate in a Cool Temperate Climate*, Forest & Wood Products Australia Limited, Melbourne.

Diakaki, C, Grigoroudis, E, & Kolokotsa, D 2008, 'Towards a multi-objective optimization approach for improving energy efficiency in buildings' *Energy and Buildings,* vol. 40, pp. 1747–1754.

Ding, GKC 2007, 'Life cycle energy assessment of Australian secondary schools', *Building Research & Information*, vol. 35, no.5, pp. 487-500.

DLMC (Davis Langdon Management Consulting) 2005, *Literature review of life cycle costing (LCC) and life cycle assessment (LCA)*, DLMC, European Commission.

DLMC (Davis Langdon Management Consulting) 2007, *Life cycle costing (LCC) as a contribution to sustainable construction: a common methodology-Literature Review*, DLMC, European Commission.

DSE 2003, *Research Matter: News from the Department of Sustainability and Environment's Urban and Regional Research*, Department of Sustainability and Environment, Australia

DSE 2007, *Options to reduce greenhouse emissions from new homes in Victoria through the building approval process*, Department of Sustainability and Environment, Australia.

ECJRC 2007, *Carbon Footprint-what it is and how to measure it*, European Commission Joint Research Centre, Luxembourg, viewed on 2nd August 2011 < lct.jrc.ec.europa.eu>.

ECJRC 2009, *International Reference Life Cycle Data System (ILCD) Handbook: General guidance document for Life Cycle Assessment (LCA)*, European Commission Joint Research Centre, draft for public consultation, European Commission, Brussels.

ECJRC 2009a, *Platform project overview*, European Commission-Joint Research Centre, viewed on 12th November 2009 <lct.jrc.ec.europa.eu/eplca>.

ECJRC 2010, *International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Provisions and Action Steps*, European Commission-Joint Research Centre-Institute for Environment and Sustainability, First edition, Publications Office of the European Union, Luxembourg.

Elmroth, A & Levine, P 1983, *Air Infiltration Control in Housing*, Swedish Council for Building Research, Stockholm.

Eren, T 2007, 'A Multicriteria Scheduling with Sequence-Dependent Setup Times' *Applied Mathematical Sciences*, vol. 1, no. 58, pp. 2883–2894.

Fabrycky, WJ & Blanchard, BS 1991, *Life cycle cost and economic analysis*, Prentice Hall, Englewood Cliffs, NJ.

Ferguson, I, La Fontaine, B, Vinden, P, Bren, L, Hateley, R & Hermesec, B 1996, *Environmental Properties of Timber*, Research Paper, Australian government and Forest & Wood Products Research & Development Corporation, Melbourne.

Finnveden, G 1999, *A Critical Review of Operational Valuation/Weighting Methods for Life Cycle Assessment,* AFR-Report 253, Swedish Environmental Protection Agency, Stockholm, Sweden

Fonseca, CM & Fleming, PJ 1998, *Multiobjective Optimization and Multiple Constraint Handling with Evolutionary Algorithms–Part I: A Unified Formulation*, IEEE Transactions on Systems, Man, and Cybernetics-Part A: Systems and Humans, vol. 28, no. 1.

Frenette, CD, Bulle, C, Beauregard, R, Salenikovice, A & Derome, D 2010, 'Using life cycle assessment to derive an environmental index for light-frame wood wall assemblies', *Building and Environment*, vol. 45, no. 10, pp. 2111-22.

Fuller, S & Petersen, S 1996, *Life-Cycle Costing Manual for the Federal Energy Management Program, NIST Handbook 135*, 1995 edition, U.S. Department of Commerce, Technology Administration and NIST.

FWPRDC (Forest & Wood Products Research & Development Corporation) 2001, *Timber Strip Floors - Fixing & Finishing Edition 1*, National Timber Development Council and FWPRDC, Melbourne.

FWPRDC (Forest & Wood Products Research & Development Corporation) 2002, *R-values for Timber Framed Building Elements (Edition 1.1)*, National Timber Development Council and FWPRDC, Melbourne.

FWPRDC (Forest & Wood Products Research & Development Corporation) 2003, 'Environmental Benefits of Building with Timber', *National Timber Development Program, Technical Report,* Issue 2, FWPRDC, Melbourne.

Garnaut, R 2008, *The Garnaut Climate Change Review: Final Report,* viewed on 7th November 2008, <www.garnautreview.org.au>.

GBCA (Green Building Council of Australia), 2008, *Dollars and Sense of Green Building 2008 Editions*, Green Building Council of Australia, viewed on 25th October 2008, <www.gbca.org.au>.

GBCA (Green Building Council of Australia) 2012, *Green Star overview*, Green Building Council of Australia, viewed on 12th January 2012, <www.gbca.org.au>.

Glick, S & Guggemos, AA 2010, 'Life-cycle assessment and life-cycle cost as collaborative tools in residential heating system selection', *Journal of Green Building,* vol.5, no. 3, pp. 107-115.

Glucha, P & Baumann, H 2004, 'The life cycle costing (LCC) approach: a conceptual discussion of its usefulness for environmental decision-making' *Building and Environment*, vol. 39, pp. 571 – 580.

Gold, S & Rubik, F 2009, 'Consumer attitudes towards timber as a construction material and towards timber frame houses–selected findings of a representative survey among the German population', *Journal of Cleaner Production*, vol. 17, no.1, pp. 303-309.

Grant, T & Carre, A 2009, *LCA course lecture note*, RMIT University, Melbourne.

Grant, T & Peters, G 2008, *Best Practice Guide to Life Cycle Assessment in Australia*, Australian Life Cycle Assessment Society, Australia.

Grant, T 1999, *Life Cycle Assessment Australian Data Inventory Project Summary Report*, Centre for Design at RMIT University, Melbourne.

Green Rate 2011, *Deemed to Satisfy - Lighting, electrical, 6-Star…,* Green Rate, australia, viewed on 22nd August 2011, <www.greenrate.com.au>.

Grodzevich, O & Romanko, O 2006, 'Normalization and Other Topics in MultiObjective Optimization', in *Proceedings of the Fields–MITACS Industrial Problems Workshop*, 2006.

Guinée, JB, Gorrée, M, Heijungs, R, Huppes, G, Kleijn, R, Koning, A. de, Oers, L van, Wegener SA, Suh, S, Udo de Haes, HA, Bruijn, H de, Duin, R van & Huijbregts, MAJ, 2002, *Handbook on life cycle assessment: Operational guide to the ISO standards*, Kluwer Academic Publishers, Dordrecht.

Hamilton, M, Brown, M & Nolan, G 2008, *Comparing the Biodiversity Impacts of Timber and Other Building Materials*, In Market Knowledge & Development, Project no: PR07.1050, Forest & Wood Products Australia, Melbourne.

Hammond, GP & Jones, CI 2008, *Inventory of Carbon & energy,* Version 1.6a, University of Bath, UK.

Hani, A & Koiv, T-A 2012, 'Optimization of Office Building Façades in a Warm Summer Continental Climate', *Smart Grid and Renewable Energy*, 2012, vol. 3, pp. 222-230.

Hauschild, MZ 2005, 'Assessing environmental impacts in a life-cycle perspective', *Environmental Science and Technology*, vol.39, no.4, pp. 81a-88a.

Hawe, G & Sykulski, J 2008, 'Scalarizing cost-effective multi-objective optimization algorithms made possible with kriging' *International Journal for Computation and Mathematic*s, vol. 27, no. 4, pp. 836-844.

Henriksen, JE 2006, 'The Value of Design in Reducing Energy Use and CO2-e Impact Over the Life Cycle Of a Detached Dwelling in Temperate Climate', Master's Thesis, University of Newcastle, Australia.

Horvath, A 1997, 'Estimation of Environmental Implications of construction materials and Designs Using LCA Techniques', PhD Thesis, Carnegie Mellon University, Pittsburgh, Pennsylvania.

Hyland, J 2011, *Price comparison report update 2011*, Office of the Tasmanian Economic Regulator, Tasmania, Australia.

ICANZ (Insulation Council of Australia and New Zealand) 2009, *Insulation Handbook, Part 1: Thermal Performance*', ICANZ, New Zealand.

IPCC 2007, *Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, IPCC, Geneva, Switzerland.

ISO 2006, *ISO 14040: 2006, Environmental management - life cycle assessment - principles and management*, International Standards Organisation, Geneva.

ISO 2008, *ISO 15686: Buildings and constructed assets - Service life planning: Part 5*, International Standards Organisation, Geneva.

IST (Island Specialty Timbers) 2011, *King Billy Pine Timber and slabs*, Island Specialty Timbers, Australia, viewed on 25th April 2011 <www.islandspecialtytimbers.com.au>.

Iyer-Raniga, U & Wong, JPC 2012, 'Evaluation of whole life cycle assessment for heritage buildings in Australia', *Building and Environment,* vol. 47, pp. 138-149.

Johansson, C & Öberg, M 2001, 'Life cycle costs and affordability perspectives for multi-dwelling buildings in Sweden', *in Proceedings of 2nd Nordic Conference on Construction Economics and Organization*, Gothenburg, April 24-25, 2001.

Kahhat R, Crittenden J, Sharif F, Fonseca E, Li K, Sawhney A, & Zhang, P 2009, 'Environmental impacts over the life cycle of residential buildings using different exterior wall systems', *Journal of Infrastructure Systems* , vol. 15, no. 3, pp. 211-221.

Kapambwe, M, Ximenes, F, Vinden, P & Keenan, R 2008, *Dynamics of Carbon Stocks in Timber in Australian Residential Housing,*' in Market Access and development, Forest & Wood Products Australia Limited, Melbourne.

Khan SU & Ardil, C 2009, 'A Weighted Sum Technique for the Joint Optimization of Performance and Power Consumption in Data Centers', *International Journal of Electrical and Electronics Engineering*, vol. 3, no.1, pp. 35-40.

Khan, SU & Min-Allah, N 2011, 'A goal programming based energy efficient resource allocation in data centers', *Journal of supercomputer*, vol.61, no. 3, pp.502-519.

Khajehpour, S 2001, 'Optimal conceptual design of high-rise office buildings', PhD Thesis, Civil Engineering, University of Waterloo, Canada.

Kneifel, J 2010, 'Life-cycle carbon and cost analysis of energy efficiency measures in new commercial buildings' *Energy and Buildings*, vol. 42, no. 3, pp. 333-340.

Kolokotsa, D, Diakaki, C, Grigoroudis, E, Stavrakakis, G & Kalaitzakis, K 2009, 'Decision support methodologies on the energy efficiency and energy management in buildings,' *Earthscan Journal*, vol. 3, pp: 121-146.

Konak, A, Coit, D, & Smith, A 2006, 'Multi-objective optimization using genetic algorithms: A tutorial', *Reliability Engineering and System Safety*, vol. 91, pp: 992-1007.

Korpi, E & Ala-Risku, T 2008, 'Life cycle costing: a review of published case studies', *Managerial Auditing Journal,* vol. 23, no. 3, 2008, pp. 240-261.

Langstone, CA 2005, *Life–Cost Approach to Building Evaluation*, 2nd edition, University of New South Wales press, NSW, Australia.

Lawson, W 1996, *Timber in Building Construction-Ecological Implications: Section-1, project no. PN017b.96,* In Market Knowledge & Development, Forest & Wood Products Research & Development Corporation, Melbourne.

Leckner, M & Zmeureanu, R 20011, 'Life cycle cost and energy analysis of a Net Zero Energy House with solar combisystem' *Applied Energy*, vol. 88, no. 1, pp. 232-241.

Lee, T, Featherston, K & Robinson, K 2006, *Rules of Thumbs for Attaining 5 Star energy Rating for Timber flooring Dwelling,* Market knowledge & Development. Melbourne, Australian Government, and Forest and Wood Products Research and Development Corporation.

Levander, E, Schade, J & Stehn, L 2009, 'Methodological and other uncertainties in life cycle costing', in *Performance Improvement in Construction Management*, Ed: B. Atkin, London and New York, pp. 233-246.

LINDO systems 2012, *About LINDO Systems*, LINDO systems, viewed on July 2012, <www.lindo.com>.

Lippke, B, Wilson, J, Perez-Garcia, J, Bowyer, J & Meil, J 2004, 'CORRIM: Life-Cycle Environmental Performance of Renewable Building Materials', *Forest Products*, vol. 54, no. 6, pp. 8-19.

Ljungberg, LY 2007, 'Materials selection and design for development of sustainable products', *Materials & Design*, vol. 28, no. 2, pp. 466–79.

Maddox, B & Nunn, J 2003, *LCA Fact Sheet: Life cycle analysis of clay brick housing based on a typical project home*, the Centre for Sustainable Technology, the University of Newcastle.

McLeod, P & Fay, R 2010, 'Costs of improving the thermal performance of houses in a cool-temperate climate', *Architectural Science Review*, vol. 53, no. 3, pp. 307-314.

McLeod, P & Fay, R 2011, 'The cost effectiveness of housing thermal performance improvements in saving CO2-e', *Architectural Science Review*, vol. 54, no.2, pp. 117-123.

Mithraratne, N 2001, 'Life cycle energy requirements of residential buildings in New Zealand', PhD thesis, University of Auckland, New Zealand.

Mithraratne, N & Vale, B 2004, 'Life cycle analysis model for New Zealand houses', *Building and Environment*, vol. 39, no. 4, pp. 483-492.

Mithraratne, N & Vale, B 2004a, 'Optimum Specification for New Zealand Houses', *in proceedings: International Conference on Sustainability Engineering and Science*, 6-9th July 2004, Auckland.

Moore, T & Morrissey, J 2010, 'Affordable zero emission housing: Through life cost-benefit analysis to identify policy pathways for residential new-build in Melbourne, Australia', in Proceeding Australasian Housing Researchers Conference, November 17-19, Auckland.

Moore, T, Morrissey, J & Horne, R 2010, 'Cost benefit pathways to zero emission housing: Implications for household cash-flows in Melbourne', in Proceedings in NZSSES Transitions to sustainability conference, Auckland, New Zealand.

Morrissey, J & Horne, RE 2011, 'Life cycle cost implications of energy efficiency measures in new residential buildings', *Energy and Buildings*, vol. 43, no. 4, pp. 915-24.

Murata, T & Ishibuchi, H 1996, 'Multiobjective genetic algorithm and its application to flow-shop scheduling', *International Journal of Computers and Engineering*, vol. 30, no. 4, pp. 957-968.

Murata, T, Ishibuchi, H & Gen, M 2001, ‘Specification of genetic search directions in cellular multiobjective genetic algorithms’, *In Proceedings of First International Conference on Evolutionary Multi-Criterion Optimization*, pp. 82-95.

Musch, J 2008, 'Design optimization of sustainable panel system using Hybrid/synthetic fibre reinforced polymer composites', Masters Thesis, Michigan State University.

Nebel, B 2006, *White Paper-Life cycle assessment and the building and construction industry*, Beacon Pathway Limited, New Zealand.

Nemry, F, Uihlein, A, Colodel, CM, Wetzel, C, Braune, A, Wittstock, B, Hasan, I, Kreißig, J, Gallon, N, Niemeier, S & Frech, Y 2010, ‘Options to reduce the environmental impacts of residential buildings in the European Union-Potential and costs’, *Energy and Buildings*, vol. 42, pp. 976-984.

Newton, PW, Baum S, Bhatia, K, Brown, SK, Cameron, AS, Foran, B, Grant, T, Mak SL, Memmott, PC, Mitchell, VG, Neate, KL, Pears, A, Smith, N, Stimson RJ, Tucker, SN & Yencken, D 2001, *Human Settlements', in Australia State of the Environment Report 2001 (Theme Report)*, CSIRO Publishing on behalf of the Department of the Environment and Heritage, Canberra.

Newton P, Hampson, K & Drogemuller, R 2009, *Technology, Design and Process Innovation in the Built Environment*, Taylor & Francis, New York.

NHBC 2010, *2nd State of Supply Report’ National Housing Building Council*, ISSN 1836-215X, Commonwealth of Australia: Canberra. ISSN

Nissinen, A, Grönroos, J, Heiskanen, E, Honkanen, A, Katajajuuri, JM, Kurppa, S, Mäkinen, T, Mäenpää, I, Seppälä, J, Timonen, P, Usva, K, Virtanen, Y & Voutilainen, P 2007, 'Developing benchmarks for consumer-oriented life cycle assessment-based environmental information on products, services and consumption patterns', *Journal of Cleaner Production*, vol. 15, pp. 538-549.

OCS 2001, *A Guide to Construction Cost Sources*, Ontario Construction Secretariat, Ontario, Toronto.

Ortiz, O, Castells, F & Sonnemann, G 2008, 'Sustainability in the construction industry: A review of recent developments based on LCA', *Construction and Building Materials*, vol. 23, no. 1, pp. 28-39.

Ortiz O, Castells F & Sonnemann G 2010, 'Life cycle assessment of two dwellings: One in Spain, a developed country, and one in Colombia, a country under development', *Science of The Total Environment,* vol. 408, pp. 2435-2443.

Oswald, G 2003, 'Ökologische Bewertung im Holzwohnbau', Dissertation, TU-Graz.

Petersen AK & Solberg B 2005, 'Environmental and economic impacts of substitution between wood products and alternative materials: a review of micro-level analyses from Norway and Sweden' *Forest Policy and Economics,* vol. 7, pp. 249-259.

Potting, J & Blok, K 1995, 'Life-cycle assessment of four types of floor covering', *Journal of Cleaner Production*, vol. 3, no. 4, pp: 201-213.

QUT 2011, *Design Standards and Guidelines-version E6A0*, Facilities Management, Queensland University of Technology, Australia.

Rajagopalan, N, Bilec, M & Landis, A 2010, 'Residential Life Cycle Assessment Modeling: Comparative Case Study Of Insulating Concrete Forms And Traditional Building Materials', *Journal of Green Building*, vol. 5, no. 3, pp. 95-106.

Rate Inflation 2011, *Historical Inflation Rates for Australia*, Rate Inflation, Australia, viewed on 20th November 2011, <www.rateinflation.com>.

Rawlinsons 2009, *Rawlinson's Australian Construction Handbook*, Rawlinson's Publishing, Perth, Western Australia.

Rawlinsons 2010, *Rawlinsons Construction Cost Guide 2010*, 18th edition, Rawlinsons Publishing, Perth, Western Australia.

Reap, J, Roman, F, Duncan, S & Bras, B 2008, 'A survey of unresolved problems in life cycle assessment', *International Journal of Life Cycle Assessment*, vol. 13, pp. 290–300.

Rebitzer, G, Ekvall, T, Frischknecht, R, Hunkeler, D, Norris, G, Rydberg, T, Schmidt, WP, Suh, S, Weidema, BP & Pennington, DW 2004, 'Life cycle assessment: Part 1:

Framework, goal and scope definition, inventory analysis, and applications', *Environment International* vol. 30, no. 5, pp. 701-720.

Ren, H, Zhou, W, Nakagami, K, Gao, W & Wu, Q 2010, 'Multi-objective optimization for the operation of distributed energy systems considering economic and environmental aspects', *Applied Energy,* vol. 87, no. 12, pp. 3642-3651.

Robinson, J 1986, 'Life cycle costing in buildings: a practical approach', *Australian Institute of Building Papers*, vol. 1, pp. 13-28.

Rouwette, R 2010, *LCA of Brick Products: Life Cycle Assessment*, Reported by Think Brick Australia, Energetics, Melbourne.

Roy, P, Nei, D, Orikasa, T, Xu, Q, Okadome, H, Nakamura, N & Shiina, T 2009, 'A review of life cycle assessment (LCA) on some food products', *Journal of Food Engineering*, vol. 90, pp. 1–10.

Santamouris, M, Mihalakakou, G, Argiriou, A & Asimakopoulos, D 1996, 'On the Efficiency of Night Ventilation Techniques for Thermostically Controlled Building,' *Solar Energy*, vol. 56, no. 6, pp. 479-483.

Schade, J 2007, *Life cycle cost calculation models for buildings: Open Information Environment for Knowledge-Based Collaborative Processes throughout the Lifecycle of a Building*, viewed on 5th august 2011, <www.inpro-project.eu>.

Schenck, R 2005, *Why LCA,* Building Design and Construction, Supplement, 4–5.

SEAV no date, *Insulation Type Fact sheet*, Sustainable Energy Authority Victoria, Melbourne (www.sustainability.vic.gov.au).

SEAV 2002, *Energy Smart Housing Manual*, (Sustainable Energy Authority Victoria), Melbourne.

Seo, S, Tucker, S, Ambrose, M, Mitchell, P & Wang, CH 2006, *Technical Evaluation of Environmental Assessment Rating Tools*, Project No. PN 05.1019, Forest and Wood Products Research and Development Corporation, Melbourne, Australia.

Shuqing, W 2005, 'A Scenario-Based Multiobjective Optimization Method for Water Resources Management', Master's Thesis, University of Regina, Saskatchewan.

Snodgrass, K 2008, *Life-cycle cost analysis for buildings is easier than you thought United States Department of Agriculture (USDA)*, Missoula Technology and Development Centre, Missoula.

Staines, A 2004, *The Australian House Building Manual*, 4th edition, Pinedale Press, Queensland, Australia.

Standards Australia 1992, *Design and installation of sheet roof and wall cladding*, AS 1562, SAI Global, Sydney.

Standards Australia 1999, *Life cycle costing-an application guide*, AS/NZS 4536, SAI Global, Sydney.

Standards Australia 2011, *Structural design actions, Part 2: wind actions*, AS/NZS 1170.2:2011, SAI Global, Sydney.

Standards Australia 2011a, *Performance of electrical appliances-air conditioners and heat pumps*, AS/NZS 3823.2, SAI Global, Sydney.

Sterner, E 2002, 'Green procurement of building: Estimation of life cycle cost and environmental impact', PhD thesis, Lulea University of Technology, Sweden.

Szalay, Z 2007, 'Life Cycle Environmental Impacts of Residential Buildings', Ph.D. Thesis, Budapest University of Technology and Economics, Budapest, Hungary.

Tan, RR 2005, 'Application of symmetric fuzzy linear programming in life cycle assessment' *Environmental Modelling & Software*, vol. 20, no.10, pp. 1343-1346.

Tharumarajah, A & Grant, T 2006, 'Australian National Life Cycle Inventory Database: Moving Forward', *in proceedings of the 5th ALCAS Conference*, Melbourne, Australia.

The MathWorks 2011, *Optimization Toolbox 6.0*, The MathWorks, viewed on 10th July 2012, <www.mathworks.com>.

Thiers, S & Peuportier, B 2008, 'Thermal and environmental assessment of a passive building equipped with an earth-to-air heat exchanger in France,' *Solar Energy*, vol. 82, no.9, pp. 820-31.

Thoft-Christensen, P 2010, “Life-Cycle Cost-Benefit analysis: Present and in the future” Aalborg University, Aalborg, Denmark.

Thormark, C 2006, ‘The effect of material choice on the total energy need and recycling potential of a building’, *Building and Environment*, vol. 41, no.8, pp. 1019–1026.

Wang, W 2005, ‘A simulation-based optimization system for green building design’, PhD Thesis, Concordia University, Montreal, Canada.

Williamson, T, Olweny, M, Moosmayer, V, Pullen, S & Bennetts, H 2001, *The Environmentally Friendly Housing using timber-principles*, National Timber Development Council and the Forest and Wood Products Research and Development Corporation, Melbourne.

Winkler, H, Spalding-Fecher, R, Tyani, L & Matibe, K 2002, ‘Cost-benefit analysis of energy efficiency in urban low-cost housing’, *Development Southern Africa*, vol. 19, No. 5, pp. 593-614.

Woodard, A & Iskra, B 2006, *The Environmental Impact of Building Materials, A Discussion Paper of Victorian Native Forest Timbers*, Victorian Association of Forest Industries, Victoria, Australia.

Wood products Victoria 2007, *Pocket Span Table Book*, Wood products Victoria, Australia.

Ximenes, FA, Gardner, WD & Cowie AL 2008, ‘The decomposition of wood products in landfills in Sydney, Australia’ *Waste Management*, vol. 28, no. 11, pp. 2344-54.

Xing, S, Xu, Z & Jun, G 2008, 'Inventory analysis of LCA on steel- and concrete-construction office buildings', *Energy and Buildings*, vol. 40, pp. 1188–1193.

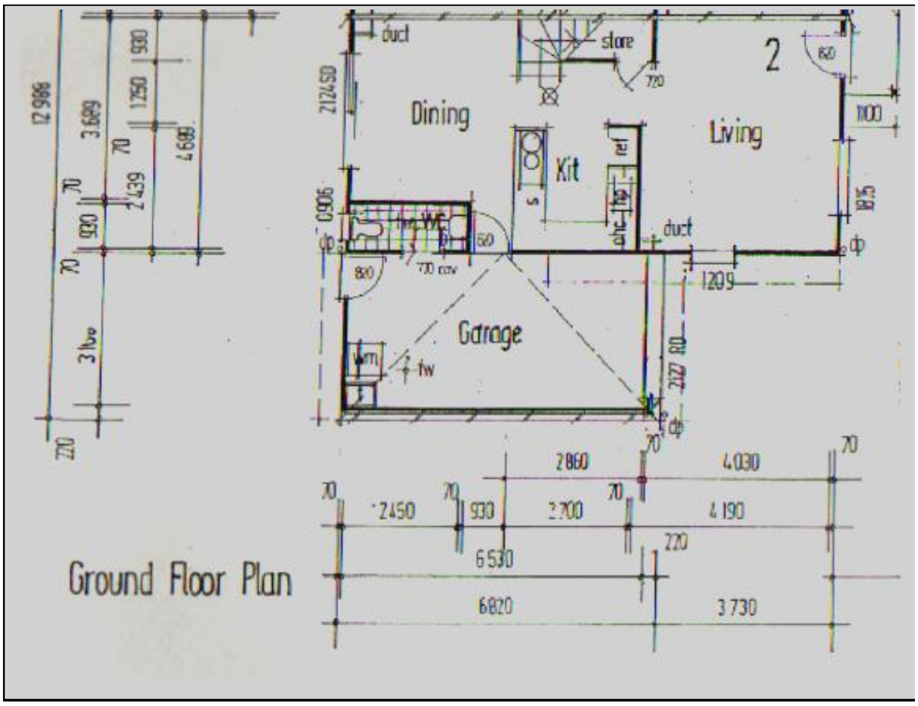
Yellishetty, M, Ranjith, PG, Tharumarajah, A & Bhosale, S 2009, ‘Life cycle assessment in the minerals and metals sector: a critical review of selected issues and challenges’, *International Journal of Life Cycle Assessment*, vol. 14, pp. 257-267.

Zacharia, JAL 2003, 'Towards sustainable homes through optimization: An approach to balancing life cycle environmental impacts and life cycle costs in residential buildings', PhD Thesis, University of Toronto, Canada.

ZWSA 2004, *Background Paper to South Australia's Waste Strategy 2005–2010, Zero Waste SA*, South Australia.

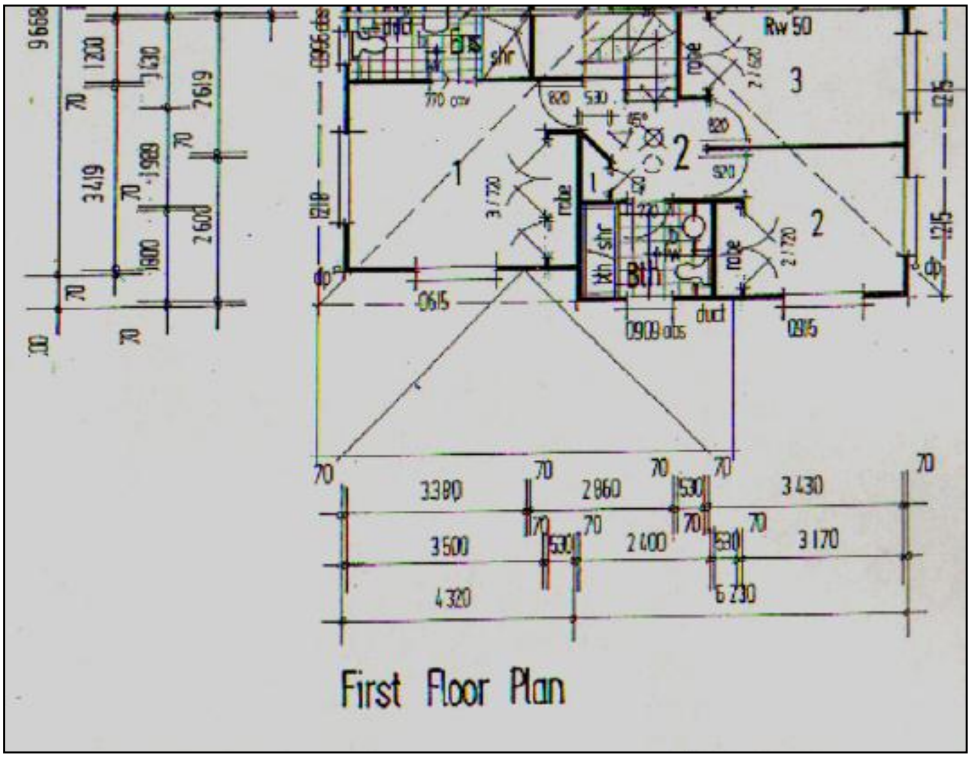
APPENDICES

Appendix 4.A: Case study house plan (Ground floor)



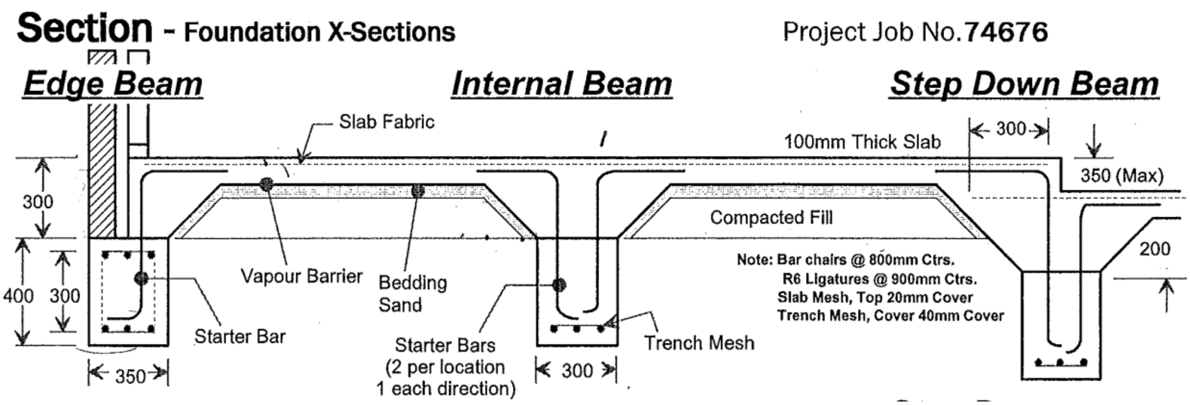
(Source: Jerrin Designs: Member of Building Designers Association of Queensland Inc., Job No. 585.02)

Appendix 4.B: Case study house plan (First floor)



(Source: Jerrin Designs: Member of Building Designers Association of Queensland Inc., Job No. 585.02)

Appendix 4.B1: Foundation X-Sections



(Source: Foundation Design Report for Jerrin Designs by Soiltest Australia Engineering Service Pty Ltd 2006, Brisbane City Council area, Project No. 74676)

Appendix 4.C: BOQ of elemental materials for case study house

Data description	Original dimension	
	Unit	Quantity
Excavation for footings	m²	19.8
Foundation Concrete	tonne	49.2
Reinforcement	kg	971
Floor Bearers (150 x 75mm)	m	145.6
Floor joists (170 x 50mm)	m	229
Floor tiling area	m²	14.9
Ply wood (floor deck)	m²	79.2
Floor area	m²	79.2
External wall (FC sheet)	m²	79.7
Building paper (External wall)	m	100.85
Brick (Wall)	m²	45
Cement Mortar for brick wall	kg	1439
Base plaster for brick wall	kg	1254
Studs (70 X 35mm)	m	750
Top and Bottom Plate	m	191.5
Plasterboard (internal wall)	m²	176
Wall tiling area	m²	40.4
Painting (total external wall)	m²	150.2
Painting (total internal wall)	m²	215
Windows area	m²	10.6
Doors area	m	25.09
Doors and windows painting area	m²	35.73
Garage roller door area	m²	5.67
Roof top for painting (area)	m²	125
Concrete roof tiles (area)	m²	125
Ceiling (plasterboard)	m²	123.2
Ceiling insulation (excluding garage)	m	112.7
Sisilation/sarking (fixed over Purlin)	m²	138.4
Roof framing	m³	1.86
Ceiling Cornices	m	137.75

Appendix 4.D: Scaling factor and weighted unit mass of major materials used

Name of the material	Unit mass	Unit mass	Unit mass	Density	References
	kg/unit	kg/m	kg/m²	kg/m³	
Concrete (footings & beams)	-	-	-	2400	Wood products Victoria 2007
Mortar cement	-	-	32	1860	Bajpai et al 2009
Brick	3	-	-		Lawson 1996
Hardwood bearers	-	-	-	800	Lawson 1996
Particleboard	-	-	-	630	Lawson 1996
Softwood weatherboard	-	-	-	550	Lawson 1996
Polystyrene	-	-	-	19	Lawson 1996
Softwood stud	-	-	-	550	Lawson 1996
Polyethylene (dpc .5 gauge)	-	-	0.49	-	Lawson 1996
Wall tile	0.05	-	12.8	-	Lawson 1996
Sarking	-	-	0.29	-	Lawson 1996
Plasterboard	-	-	7.5	-	Wood products Victoria 2007
Paint	-	-	2.4	-	Lawson 1996
Concrete tile	-	-	54	-	Wood products Victoria 2007
T&G hardwood (19mm)	-	-	12	-	Wood products Victoria 2007
Glass 6.68mm	-	-	16	-	Lawson 1996
Ply wood (12mm)	-	-	6.5	-	Wood products Victoria 2007
Glass fibre batt	-	-	12	-	Hammond & Jones 2008
FC Sheet (6mm)	-	-	11		Wood products Victoria 2007
AAC Concrete block	-	-	-	700	Lawson 1996
Polystyrene, expanded	-	-	-	23	Hammond & Jones 2008
Metal roof (.75mm)	-	-	10	-	Wood products Victoria 2007

Appendix 4.E: Major elemental costs for case study house (Rawlinsons 2010)

No.	Description	Unit	Quantity	Rate/unit	Total (AUD)
1	Strip footing concrete	m^3	7.94	226	1794
2	FC sheet (external wall)	m^2	79.72	30.8	2455
3	Floor tiles in wet areas	m^2	14.98	40	599
4	Floor bearers (150x75mm)	m	145.6	13.05	1900
5	Concrete roof tiles	m^2	125.8	32.3	4064
6	Wall tiling	m^2	40.5	40	1618
7	Concrete roof tiles	m^2	125.8	32.3	4064
8	Ply wood (floor deck)	m^2	79.2	34	2692
9	T&G timber floor	m^2	79.2	51.8	4101
10	Double glazed window	m^2	10.6	630	6709
11	Ceiling cornice	m	117.8	12.5	1471
12	R1 Glass Fibre Batt (External wall)	m^2	100.86	6.2	811.8
13	Sisilation (RFL) fixed over purlin	m^2	138.4	10.9	1508.5
14	R2.5 Glass wool Batt for Ceiling	m^2	112.73	9.85	1110.3
15	Carpet	m^2	79.18	30	2375.4
16	Carpet underlay	m^2	79.18	9.5	752.2
17	Paint Alkyd enamel (internal wall)	m^2	214.8	8.3	1782.8
18	Paint Alkyd enamel (external wall)	m^2	79.18	9.55	756.2
19	Acrylic timber finish (Door area)	m^2	25.1	6.55	166.8

Appendix 4.E1: Labour constants and wage rate for case study house (Rawlinsons 2010)

- Painting labour constant: one m^2 requires .2 Tradesman hours, and wage rate is 46$/hour.
- Door fixing labour constant: 1.2 tradesman hour requires for 2040x820 solid door, and wage rate is 47.5$/hour.
- Brick works: Standard brickwork requires 12-tradesman hours and 4 labour hours per 100 bricks laying works, and wage rate for trades man 47$/hour and for labour 45$/hour.

Appendix 4.F: Sample *AccuRate* results for case study house

AccuRate V1.1.4.1

Nationwide House Energy Rating Scheme

Project Details	
Project Name: Brisbane Case Study_External wall	
File Name: F:\Brisbane Case study\PhD Completion\Thesis\Accurate Star Rating\Wall\3.6 star Wall.PRO	
Postcode: 4032	**Climate Zone:** 10
Design Option: Base Case	
Description:	

Client Details		
Client Name:R. Setunge & S. Setunge		
Phone:	**Fax:**	**Email:**
Postal Address:20 YARALLAH STREET		
Site Address:20 YARALLAH STREEt, Chermside, Brisbane		
Council submitted to (if known by assessor): Brisbane City Council		

Assessor Details		
Assessor Name:HAMIDUL ISLAM		**Assessor No.**
Phone:0430226515	**Fax:**	**Email:**hamidul.islam@rmit.edu.au
Assessment Date:19/09/2012		**Time:**10:53
Project Code:		
Assessor Signature:		

CALCULATED ENERGY REQUIREMENTS*

Heating	Cooling (sensible)	Cooling (latent)	Total Energy	Units
23.2	58.7	22.1	103.9	MJ/m².annum

* These energy requirements have been calculated using a standard set of occupant behaviours and so do not necessarily represent the usage pattern or lifestyle of the intended occupants. They should be used solely for the purposes of rating the building. They should not be used to infer actual energy consumption or running costs. The settings used for the simulation are shown in the building data report.

AREA-ADJUSTED ENERGY REQUIREMENTS

Heating	Cooling (sensible)	Cooling (latent)	Total Energy	Units
18.2	46.0	17.3	81.6	MJ/m².annum
Conditioned floor area		88.2 m²		

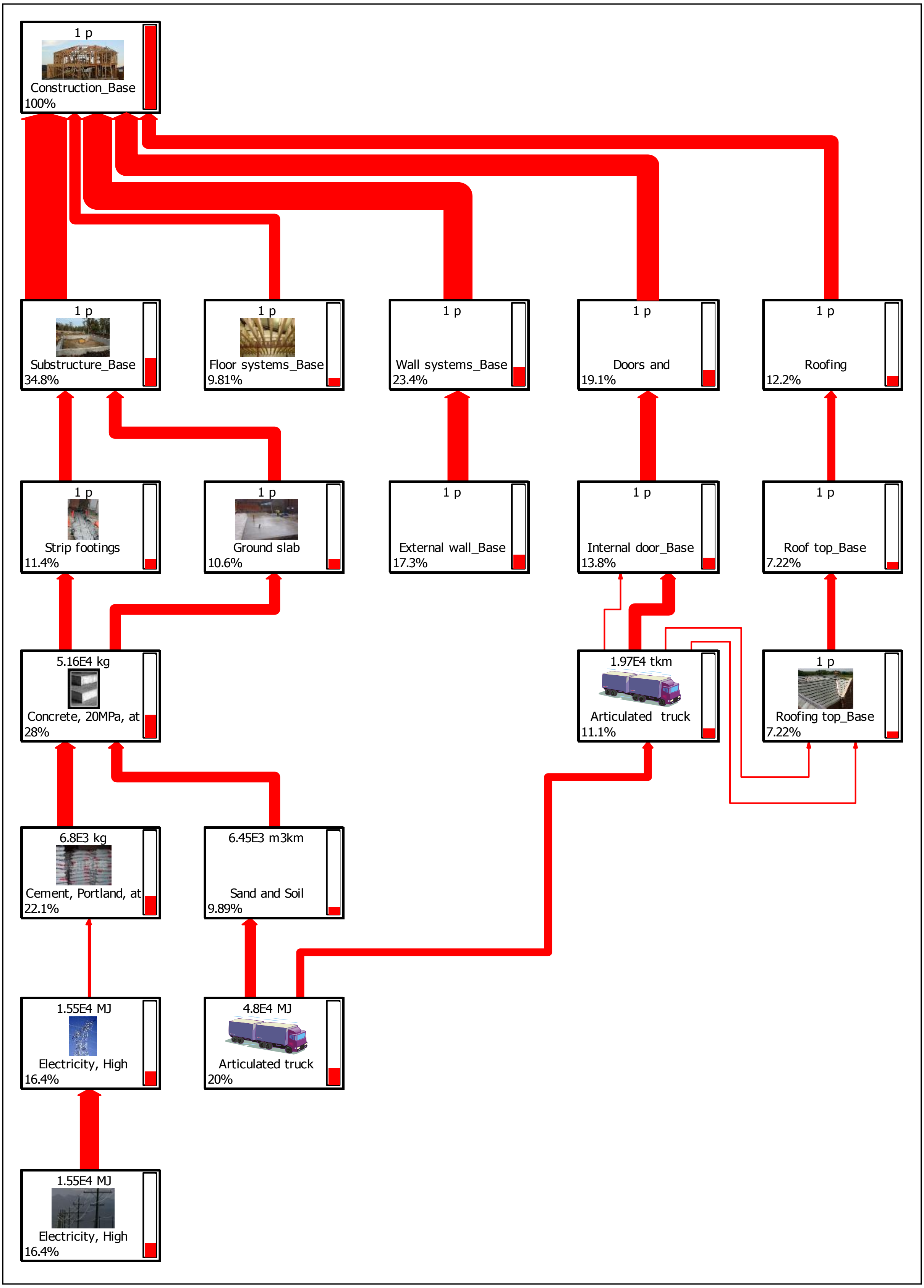
Star Rating

★★★☆ **3.6 STARS**

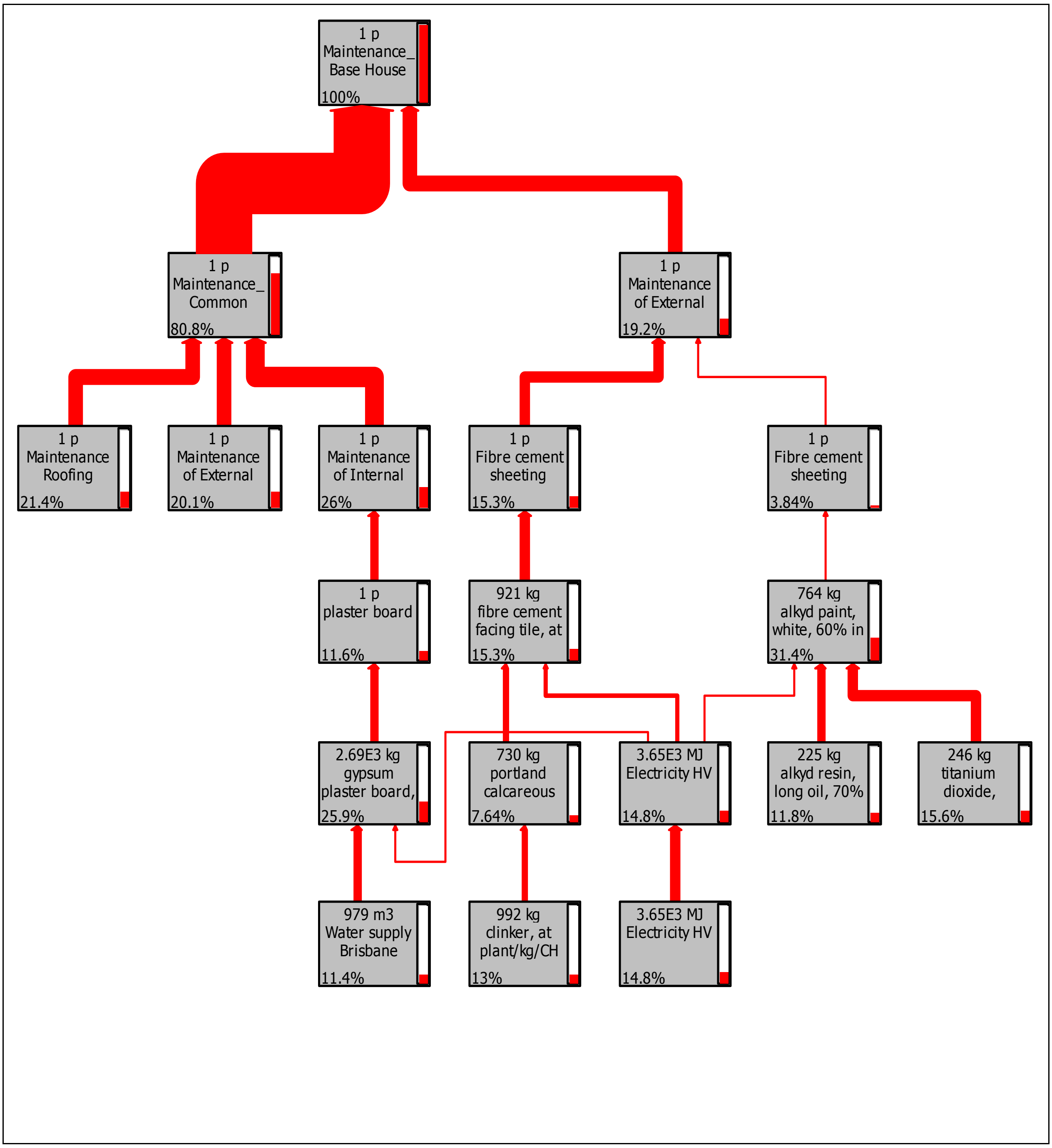
Area-adjusted star band score thresholds

1 Star	2 Stars	3 Stars	4 Stars	5 Stars	6 Stars	7 Stars	8 Stars	9 Stars	10 Stars
203	139	97	71	55	43	34	25	17	10

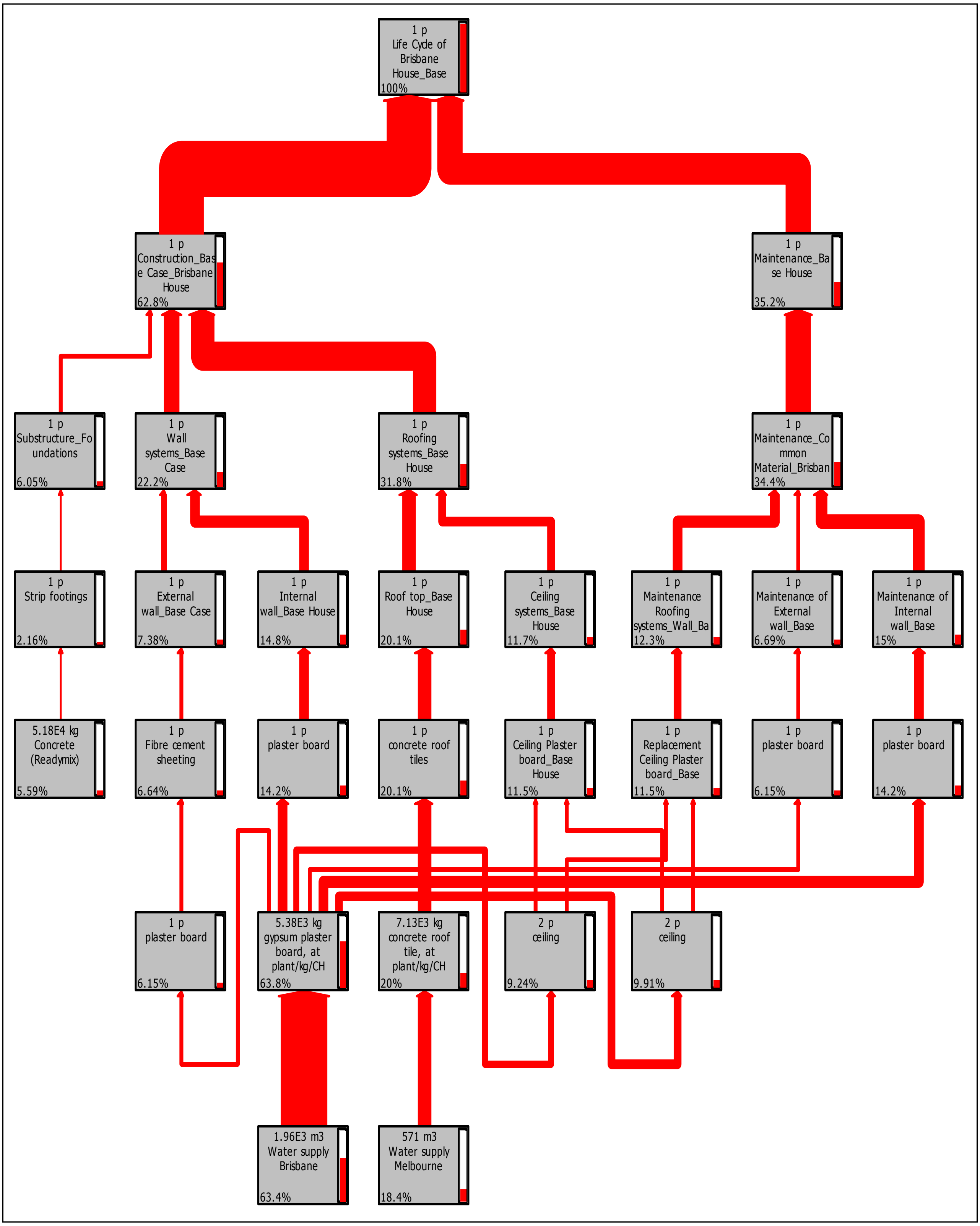
Appendix 4.G: Process tree showing relative contributions to GHG in construction phase



Appendix 4.H: Process tree showing relative contributions to GHG at maintenance



Appendix 4.I: Process tree showing relative contributions to water use whole life cycle



APPENDIX: LINDO OPTIMISATION RESULTS

Appendix 8.A: Houses with wall designs: all the effects at least as good as the "highest" value

Minimise GHG Emission

Optimisation Model:

```
!Let BH3.9 be Brick House 3.9 star design
!Let CH3.9 be Concrete House 3.9 star design
!Let FC3.9 be FC sheet House 3.9 star design
!Let PL3.9 be Pine log House 3.9 star design
!Let WB3.9 be Weatherboard House 3.9 star design
!Let BH3.8 be Brick House 3.8 star design
!Let CH3.8 be Concrete House 3.8 star design
!Let FC3.8 be FC sheet House 3.8 star design
!Let PL3.8 be Pine log House 3.8 star design
!Let WB3.8 be Weatherboard House 3.8 star design
!Let BH3.7 be Brick House 3.7 star design
!Let CH3.7 be Concrete House 3.7 star design
!Let FC3.7 be FC sheet House 3.7 star design
!Let PL3.7 be Pine log House 3.7 star design
!Let WB3.7 be Weatherboard House 3.7 star design
!Let CH3.6 be Concrete House 3.6 star design
!Let FC3.6 be FC sheet House 3.6 star design
!Let WB3.6 be Weatherboard House 3.8 star design
!Let BC be Base case
!
!Objective: Minimize Total GHG Emissions
!
Min 75.2 BH3.9 + 75.0 CH3.9 + 71.5 FC3.9 + 65 PL3.9 + 69.8 WB3.9+ 76.8 BH3.8 + 75.7 CH3.8 + 72.3 FC3.8 + 65.9 PL3.8 + 70.8 WB3.8 + 77.8 BH3.7 + 74.5 CH3.7 + 74.5 FC3.7 + 66.7 PL3.7 + 72.6 WB3.7 + 77.6 CH3.6 + 75.5 FC3.6 + 73.7 WB3.6+ 76.2 BC
!
Subject to
!the following constraints
!
!CED (GJ)
1071 BH3.9 + 1043 CH3.9 + 1054 FC3.9 + 1013 PL3.9 + 1042 WB3.9 + 1071 BH3.8 + 1053 CH3.8 + 1054 FC3.8 + 1024 PL3.8 + 1042 WB3.8 + 1086 BH3.7+ 1070 CH3.7 + 1055 FC3.7 + 1037 PL3.7 + 1046 WB3.7 + 1079 CH3.6 + 1069 FC3.6 + 1060 WB3.6 + 1078 BC <= 1079
!
!Water Use (kL)
3098 BH3.9 + 3106 CH3.9 + 3103 FC3.9 + 3068 PL3.9 + 3078 WB3.9 + 3097 BH3.8 + 3107 CH3.8 + 3102 FC3.8 + 3068 PL3.8 + 3078 WB3.8 + 3098 BH3.7 + 3108 CH3.7 + 3102 FC3.7 + 3069 PL3.7 + 3077 WB3.7 + 3108 CH3.6 + 3102 FC3.6 + 3078 WB3.6 + 3103 BC <= 3108
!
!Waste impact (Tonne)
96.8 BH3.9 + 88.1 CH3.9 + 81.6 FC3.9 + 82.6 PL3.9 + 78.7 WB3.9 + 96.3 BH3.8 + 88.0 CH3.8 + 81.8 FC3.8 + 82.5 PL3.8 + 78.7 WB3.8 + 96.3 BH3.7 + 87.9 CH3.7 + 80.8 FC3.7 + 82.4 PL3.7 + 78.2 WB3.7 + 87.9 CH3.6 + 80.8 FC3.6 + 78.2 WB3.6 + 80.8 BC <= 96.8
!
!Life Cycle cost (AUD)
219256 BH3.9 + 218152 CH3.9 + 211795 FC3.9 + 245277 PL3.9 + 214270 WB3.9 + 216057 BH3.8 + 217388 CH3.8 + 211533 FC3.8 + 243522 PL3.8 + 214058 WB3.8 + 215665 BH3.7 + 216958 CH3.7 + 208847 FC3.7 + 243030 PL3.7 + 211421 WB3.7 + 216985 CH3.6 + 208662 FC3.6 + 210893 WB3.6 + 208656 BC <= 245277
!
!Choose at least one
BH3.9 + CH3.9 + FC3.9 + PL3.9 + WB3.9 + BH3.8 + CH3.8 + FC3.8 + PL3.8 + WB3.8 + BH3.7 + CH3.7 + FC3.7 + PL3.7 + WB3.7 + CH3.6 + FC3.6 + WB3.6+ BC >=1
!
END
!
!All binary integers
INT BH3.9
INT CH3.9
INT FC3.9
INT PL3.9
INT WB3.9
INT BH3.8
INT CH3.8
```

INT FC3.8
INT PL3.8
INT WB3.8
INT BH3.7
INT CH3.7
INT FC3.7
INT PL3.7
INT WB3.7
INT CH3.6
INT FC3.6
INT WB3.6
INT BC

Optimisation Model Results:

```
LP OPTIMUM FOUND AT STEP      2
OBJECTIVE VALUE =   65.0000000

FIX ALL VARS.(    18)  WITH RC >  0.000000E+00

NEW INTEGER SOLUTION OF    65.0000000     AT BRANCH      0 PIVOT       2
BOUND ON OPTIMUM:  65.00000
ENUMERATION COMPLETE. BRANCHES=     0 PIVOTS=       2

LAST INTEGER SOLUTION IS THE BEST FOUND
RE-INSTALLING BEST SOLUTION...

       OBJECTIVE FUNCTION VALUE

       1)      65.00000

 VARIABLE        VALUE          REDUCED COST
    BH3.9         0.000000         75.199997
    CH3.9         0.000000         75.000000
    FC3.9         0.000000         71.500000
    PL3.9         1.000000         65.000000
    WB3.9         0.000000         69.800003
    BH3.8         0.000000         76.800003
    CH3.8         0.000000         75.699997
    FC3.8         0.000000         72.300003
    PL3.8         0.000000         65.900002
    WB3.8         0.000000         70.800003
    BH3.7         0.000000         77.800003
    CH3.7         0.000000         74.500000
    FC3.7         0.000000         74.500000
    PL3.7         0.000000         66.699997
    WB3.7         0.000000         72.599998
    CH3.6         0.000000         77.599998
    FC3.6         0.000000         75.500000
    WB3.6         0.000000         73.699997
       BC         0.000000         76.199997


      ROW   SLACK OR SURPLUS     DUAL PRICES
       2)        66.000000         0.000000
       3)        40.000000         0.000000
       4)        14.200002         0.000000
       5)         0.000000         0.000000
       6)         0.000000         0.000000

NO. ITERATIONS=       2
BRANCHES=    0 DETERM.=  1.000E    0
```

Appendix 8.B: Houses with wall designs: all the effects at least as good as the "lowest" value

Minimise GHG Emission

Optimisation Model:

```
!Let BH3.9 be Brick House 3.9 star design
!Let CH3.9 be Concrete House 3.9 star design
!Let FC3.9 be FC sheet House 3.9 star design
!Let PL3.9 be Pine log House 3.9 star design
!Let WB3.9 be Weatherboard House 3.9 star design
!Let BH3.8 be Brick House 3.8 star design
!Let CH3.8 be Concrete House 3.8 star design
!Let FC3.8 be FC sheet House 3.8 star design
!Let PL3.8 be Pine log House 3.8 star design
!Let WB3.8 be Weatherboard House 3.8 star design
!Let BH3.7 be Brick House 3.7 star design
!Let CH3.7 be Concrete House 3.7 star design
!Let FC3.7 be FC sheet House 3.7 star design
!Let PL3.7 be Pine log House 3.7 star design
!Let WB3.7 be Weatherboard House 3.7 star design
!Let CH3.6 be Concrete House 3.6 star design
!Let FC3.6 be FC sheet House 3.6 star design
!Let WB3.6 be Weatherboard House 3.8 star design
!Let BC be Base case
!
!Objective: Minimize Total GHG Emissions
!
Min 75.2 BH3.9 + 75.0 CH3.9 + 71.5 FC3.9 + 65 PL3.9 + 69.8 WB3.9+ 76.8 BH3.8 + 75.7 CH3.8 + 72.3 FC3.8 + 65.9 PL3.8 +
70.8 WB3.8 + 77.8 BH3.7 + 74.5 CH3.7 + 74.5 FC3.7 + 66.7 PL3.7 + 72.6 WB3.7 + 77.6 CH3.6 + 75.5 FC3.6 + 73.7 WB3.6+ 76.2
BC
!
Subject to
!the following constraints
!
!CED (GJ)
1071 BH3.9 + 1043 CH3.9 + 1054 FC3.9 + 1013 PL3.9 + 1042 WB3.9 + 1071 BH3.8 + 1053 CH3.8 + 1054 FC3.8 + 1024 PL3.8 +
1042 WB3.8 + 1086 BH3.7+ 1070 CH3.7 + 1055 FC3.7 + 1037 PL3.7 + 1046 WB3.7 + 1079 CH3.6 + 1069 FC3.6 + 1060 WB3.6 +
1078 BC <= 1013
!
!Water Use (kL)
3098 BH3.9 + 3106 CH3.9 + 3103 FC3.9 + 3068 PL3.9 + 3078 WB3.9 + 3097 BH3.8 + 3107 CH3.8 + 3102 FC3.8 + 3068 PL3.8
+ 3078 WB3.8 + 3098 BH3.7 + 3108 CH3.7 + 3102 FC3.7 + 3069 PL3.7 + 3077 WB3.7 + 3108 CH3.6 + 3102 FC3.6 + 3078
WB3.6 + 3103 BC <= 3068
!
!Waste impact (Tonne)
96.8 BH3.9 + 88.1 CH3.9 + 81.6 FC3.9 + 82.6 PL3.9 + 78.7 WB3.9 + 96.3 BH3.8 + 88.0 CH3.8 + 81.8 FC3.8 + 82.5 PL3.8 + 78.7
WB3.8 + 96.3 BH3.7 + 87.9 CH3.7 + 80.8 FC3.7 + 82.4 PL3.7 + 78.2 WB3.7 + 87.9 CH3.6 + 80.8 FC3.6 + 78.2 WB3.6 + 80.8 BC
<= 78.2
!
!Life Cycle cost (AUD)
219256 BH3.9 + 218152 CH3.9 + 211795 FC3.9 + 245277 PL3.9 + 214270 WB3.9 + 216057 BH3.8 + 217388 CH3.8 + 211533
FC3.8 + 243522 PL3.8 + 214058 WB3.8 + 215665 BH3.7 + 216958 CH3.7 + 208847 FC3.7 + 243030 PL3.7 + 211421 WB3.7 +
216985 CH3.6 + 208662 FC3.6 + 210893 WB3.6 + 208656 BC <= 208656
!
!Choose at least one
BH3.9 + CH3.9 + FC3.9 + PL3.9 + WB3.9 + BH3.8 + CH3.8 + FC3.8 + PL3.8 + WB3.8 + BH3.7 + CH3.7 + FC3.7 + PL3.7 +
WB3.7 + CH3.6 + FC3.6 + WB3.6+ BC >=1
!
END
!
!All binary integers
INT BH3.9
INT CH3.9
INT FC3.9
INT PL3.9
INT WB3.9
INT BH3.8
INT CH3.8
INT FC3.8
```

INT PL3.8
INT WB3.8
INT BH3.7
INT CH3.7
INT FC3.7
INT PL3.7
INT WB3.7
INT CH3.6
INT FC3.6
INT WB3.6
INT BC

<u>Optimisation Model Results</u>: No feasible results was found

Appendix 8.C: Houses of wall designs: all the effects at least as good as the "average" impacts and costs

<u>Minimise GHG Emission</u>

<u>Optimisation Model:</u>

!Let BH3.9 be Brick House 3.9 star design
!Let CH3.9 be Concrete House 3.9 star design
!Let FC3.9 be FC sheet House 3.9 star design
!Let PL3.9 be Pine log House 3.9 star design
!Let WB3.9 be Weatherboard House 3.9 star design
!Let BH3.8 be Brick House 3.8 star design
!Let CH3.8 be Concrete House 3.8 star design
!Let FC3.8 be FC sheet House 3.8 star design
!Let PL3.8 be Pine log House 3.8 star design
!Let WB3.8 be Weatherboard House 3.8 star design
!Let BH3.7 be Brick House 3.7 star design
!Let CH3.7 be Concrete House 3.7 star design
!Let FC3.7 be FC sheet House 3.7 star design
!Let PL3.7 be Pine log House 3.7 star design
!Let WB3.7 be Weatherboard House 3.7 star design
!Let CH3.6 be Concrete House 3.6 star design
!Let FC3.6 be FC sheet House 3.6 star design
!Let WB3.6 be Weatherboard House 3.8 star design
!Let BC be Base case
!
!Objective: Minimize Total GHG Emissions
!
Min 75.2 BH3.9 + 75.0 CH3.9 + 71.5 FC3.9 + 65 PL3.9 + 69.8 WB3.9+ 76.8 BH3.8 + 75.7 CH3.8 + 72.3 FC3.8 + 65.9 PL3.8 + 70.8 WB3.8 + 77.8 BH3.7 + 74.5 CH3.7 + 74.5 FC3.7 + 66.7 PL3.7 + 72.6 WB3.7 + 77.6 CH3.6 + 75.5 FC3.6 + 73.7 WB3.6+ 76.2 BC
!
Subject to
!the following constraints
!
!CED (GJ)
1071 BH3.9 + 1043 CH3.9 + 1054 FC3.9 + 1013 PL3.9 + 1042 WB3.9 + 1071 BH3.8 + 1053 CH3.8 + 1054 FC3.8 + 1024 PL3.8 + 1042 WB3.8 + 1086 BH3.7+ 1070 CH3.7 + 1055 FC3.7 + 1037 PL3.7 + 1046 WB3.7 + 1079 CH3.6 + 1069 FC3.6 + 1060 WB3.6 + 1078 BC <= 1055
!
!Water Use (kL)
3098 BH3.9 + 3106 CH3.9 + 3103 FC3.9 + 3068 PL3.9 + 3078 WB3.9 + 3097 BH3.8 + 3107 CH3.8 + 3102 FC3.8 + 3068 PL3.8 + 3078 WB3.8 + 3098 BH3.7 + 3108 CH3.7 + 3102 FC3.7 + 3069 PL3.7 + 3077 WB3.7 + 3108 CH3.6 + 3102 FC3.6+ 3078 WB3.6 + 3103 BC <= 3092
!
!Waste impact (Tonne)
96.8 BH3.9 + 88.1 CH3.9 + 81.6 FC3.9 + 82.6 PL3.9 + 78.7 WB3.9 + 96.3 BH3.8 + 88.0 CH3.8 + 81.8 FC3.8 + 82.5 PL3.8 + 78.7 WB3.8 + 96.3 BH3.7 + 87.9 CH3.7 + 80.8 FC3.7 + 82.4 PL3.7 + 78.2 WB3.7+ 87.9 CH3.6 + 80.8 FC3.6 + 78.2 WB3.6+ 80.8 BC <= 84.6
!
!Life Cycle cost (AUD)
219256 BH3.9 + 218152 CH3.9 + 211795 FC3.9 + 245277 PL3.9 + 214270 WB3.9 + 216057 BH3.8 + 217388 CH3.8 + 211533 FC3.8 + 243522 PL3.8 + 214058 WB3.8 + 215665 BH3.7 + 216958 CH3.7 + 208847 FC3.7 + 243030 PL3.7 + 211421 WB3.7+ 216985 CH3.6 + 208662 FC3.6 + 210893 WB3.6 + 208656 BC <= 218549
!

!Choose at least one
BH3.9 + CH3.9 + FC3.9 + PL3.9 + WB3.9+ BH3.8 + CH3.8 + FC3.8 + PL3.8 + WB3.8 + BH3.7 + CH3.7 + FC3.7 + PL3.7 + WB3.7 + CH3.6 + FC3.6 + WB3.6+ BC >=1
!
END
!
!All binary integers
INT BH3.9
INT CH3.9
INT FC3.9
INT PL3.9
INT WB3.9
INT BH3.8
INT CH3.8
INT FC3.8
INT PL3.8
INT WB3.8
INT BH3.7
INT CH3.7
INT FC3.7
INT PL3.7
INT WB3.7
INT CH3.6
INT FC3.6
INT WB3.6
INT BC

Optimisation Model Results:

```
LP OPTIMUM FOUND AT STEP        2
OBJECTIVE VALUE =    69.1375961

FIX ALL VARS.(    16)  WITH RC >  0.000000E+00
SET    PL3.9 TO <=      0 AT    1, BND=  -69.23     TWIN=-0.1000E+31       3
SET    PL3.8 TO <=      0 AT    2, BND=  -69.80     TWIN=-0.1000E+31       6

NEW INTEGER SOLUTION OF    69.8000031     AT BRANCH      2 PIVOT       6
BOUND ON OPTIMUM:  69.22951
DELETE    PL3.8 AT LEVEL     2
DELETE    PL3.9 AT LEVEL     1
RELEASE FIXED VARIABLES
ENUMERATION COMPLETE. BRANCHES=     2 PIVOTS=      12

LAST INTEGER SOLUTION IS THE BEST FOUND
RE-INSTALLING BEST SOLUTION...

       OBJECTIVE FUNCTION VALUE

       1)      69.80000

 VARIABLE        VALUE          REDUCED COST
    BH3.9         0.000000         75.199997
    CH3.9         0.000000         75.000000
    FC3.9         0.000000         71.500000
    PL3.9         0.000000         65.000000
    WB3.9         1.000000         69.800003
    BH3.8         0.000000         76.800003
    CH3.8         0.000000         75.699997
    FC3.8         0.000000         72.300003
    PL3.8         0.000000         65.900002
    WB3.8         0.000000         70.800003
    BH3.7         0.000000         77.800003
    CH3.7         0.000000         74.500000
    FC3.7         0.000000         74.500000
    PL3.7         0.000000         66.699997
    WB3.7         0.000000         72.599998
    CH3.6         0.000000         77.599998
    FC3.6         0.000000         75.500000
    WB3.6         0.000000         73.699997
       BC         0.000000         76.199997


      ROW   SLACK OR SURPLUS     DUAL PRICES
       2)        13.000000         0.000000
       3)        14.000000         0.000000
       4)         2.100003         0.000000
       5)      4279.000000         0.000000
       6)         0.000000         0.000000

NO. ITERATIONS=       12
BRANCHES=     2 DETERM.=  1.000E    0
```

Appendix 8.D: Houses with wall designs: all the effects at least as good as the "base case"

Minimise GHG Emission

Optimisation Model:

```
!Let BH3.9 be Brick House 3.9 star design
!Let CH3.9 be Concrete House 3.9 star design
!Let FC3.9 be FC sheet House 3.9 star design
!Let PL3.9 be Pine log House 3.9 star design
!Let WB3.9 be Weatherboard House 3.9 star design
!Let BH3.8 be Brick House 3.8 star design
!Let CH3.8 be Concrete House 3.8 star design
!Let FC3.8 be FC sheet House 3.8 star design
!Let PL3.8 be Pine log House 3.8 star design
!Let WB3.8 be Weatherboard House 3.8 star design
!Let BH3.7 be Brick House 3.7 star design
!Let CH3.7 be Concrete House 3.7 star design
!Let FC3.7 be FC sheet House 3.7 star design
!Let PL3.7 be Pine log House 3.7 star design
!Let WB3.7 be Weatherboard House 3.7 star design
!Let CH3.6 be Concrete House 3.6 star design
!Let FC3.6 be FC sheet House 3.6 star design
!Let WB3.6 be Weatherboard House 3.8 star design
!Let BC be Base case
!
!Objective: Minimize Total GHG Emissions
!
Min 75.2 BH3.9 + 75.0 CH3.9 + 71.5 FC3.9 + 65 PL3.9 + 69.8 WB3.9+ 76.8 BH3.8 + 75.7 CH3.8 + 72.3 FC3.8 + 65.9 PL3.8 + 70.8 WB3.8 + 77.8 BH3.7 + 74.5 CH3.7 + 74.5 FC3.7 + 66.7 PL3.7 + 72.6 WB3.7 + 77.6 CH3.6 + 75.5 FC3.6 + 73.7 WB3.6+ 76.2 BC
!
Subject to
!the following constraints
!
!CED (GJ)
1071 BH3.9 + 1043 CH3.9 + 1054 FC3.9 + 1013 PL3.9 + 1042 WB3.9 + 1071 BH3.8 + 1053 CH3.8 + 1054 FC3.8 + 1024 PL3.8 + 1042 WB3.8 + 1086 BH3.7+ 1070 CH3.7 + 1055 FC3.7 + 1037 PL3.7 + 1046 WB3.7 + 1079 CH3.6 + 1069 FC3.6 + 1060 WB3.6 + 1078 BC <= 1078
!
!Water Use (kL)
3098 BH3.9 + 3106 CH3.9 + 3103 FC3.9 + 3068 PL3.9 + 3078 WB3.9 + 3097 BH3.8 + 3107 CH3.8 + 3102 FC3.8 + 3068 PL3.8 + 3078 WB3.8 + 3098 BH3.7 + 3108 CH3.7 + 3102 FC3.7 + 3069 PL3.7 + 3077 WB3.7 + 3108 CH3.6 + 3102 FC3.6 + 3078 WB3.6 + 3103 BC <= 3103
!
!Waste impact (Tonne)
96.8 BH3.9 + 88.1 CH3.9 + 81.6 FC3.9 + 82.6 PL3.9 + 78.7 WB3.9 + 96.3 BH3.8 + 88.0 CH3.8 + 81.8 FC3.8 + 82.5 PL3.8 + 78.7 WB3.8 + 96.3 BH3.7 + 87.9 CH3.7 + 80.8 FC3.7 + 82.4 PL3.7 + 78.2 WB3.7 + 87.9 CH3.6 + 80.8 FC3.6 + 78.2 WB3.6 + 80.8 BC <= 80.8
!
!Life Cycle cost (AUD)
219256 BH3.9 + 218152 CH3.9 + 211795 FC3.9 + 245277 PL3.9 + 214270 WB3.9 + 216057 BH3.8 + 217388 CH3.8 + 211533 FC3.8 + 243522 PL3.8 + 214058 WB3.8 + 215665 BH3.7 + 216958 CH3.7 + 208847 FC3.7 + 243030 PL3.7 + 211421 WB3.7 + 216985 CH3.6 + 208662 FC3.6 + 210893 WB3.6 + 208656 BC <= 208656
!
!Choose at least one
BH3.9 + CH3.9 + FC3.9 + PL3.9 + WB3.9 + BH3.8 + CH3.8 + FC3.8 + PL3.8 + WB3.8 + BH3.7 + CH3.7 + FC3.7 + PL3.7 + WB3.7 + CH3.6 + FC3.6 + WB3.6+ BC >=1
!
END
!
!All binary integers
INT BH3.9
INT CH3.9
INT FC3.9
INT PL3.9
INT WB3.9
INT BH3.8
INT CH3.8
INT FC3.8
```

INT PL3.8
INT WB3.8
INT BH3.7
INT CH3.7
INT FC3.7
INT PL3.7
INT WB3.7
INT CH3.6
INT FC3.6
INT WB3.6
INT BC

Optimisation Model Results:

```
LP OPTIMUM FOUND AT STEP      22
OBJECTIVE VALUE =    76.1999969

FIX ALL VARS.(    16)  WITH RC >    20.5836

NEW INTEGER SOLUTION OF     76.1999969     AT BRANCH       0 PIVOT       22
BOUND ON OPTIMUM:   76.20000
ENUMERATION COMPLETE. BRANCHES=      0 PIVOTS=       22

LAST INTEGER SOLUTION IS THE BEST FOUND
RE-INSTALLING BEST SOLUTION...

       OBJECTIVE FUNCTION VALUE

       1)       76.20000

  VARIABLE        VALUE          REDUCED COST
     BH3.9         0.000000         75.199997
     CH3.9         0.000000         75.000000
     FC3.9         0.000000         71.500000
     PL3.9         0.000000         65.000000
     WB3.9         0.000000         69.800003
     BH3.8         0.000000         76.800003
     CH3.8         0.000000         75.699997
     FC3.8         0.000000         72.300003
     PL3.8         0.000000         65.900002
     WB3.8         0.000000         70.800003
     BH3.7         0.000000         77.800003
     CH3.7         0.000000         74.500000
     FC3.7         0.000000         74.500000
     PL3.7         0.000000         66.699997
     WB3.7         0.000000         72.599998
     CH3.6         0.000000         77.599998
     FC3.6         0.000000         75.500000
     WB3.6         0.000000         73.699997
        BC         1.000000         76.199997

      ROW   SLACK OR SURPLUS     DUAL PRICES
       2)         0.000000         0.000000
       3)         0.000000         0.000000
       4)        -0.000003         0.000000
       5)         0.000000         0.000000
       6)         0.000000         0.000000

NO. ITERATIONS=      22
BRANCHES=    0 DETERM.=   1.000E    0
```

Appendix 8.E: Houses with roof designs: all the affects at least as good as “highest” value

Minimise GHG Emission

Optimisation Model:

!Let BC be Base case
!Let MR3.9 be Metal roof house 3.9 star design
!Let MR3.6 be Metal roof house 3.6 star design
!Let SF3.9 be Skillion flat roof house 3.9 star design
!Let SF3.6 be Skillion flat roof house 3.6 star design
!Let SP3.9 be Skillion pitch roof house 3.9 star design
!Let SP3.6 be Skillion pitch roof house 3.6 star design
!Let TF3.9 be Tiled flat roof house 3.9 star design
!Let TF3.6 be Tiled flat roof house 3.6 star design
!
!Objective: Minimize Life cycle GHG (tonne CO2)
!
Min 76.2 BC + 70.3 MR3.9 + 69.9 SF3.9 + 71.7 SP3.9 + 68.2 TF3.9 + 72.8 MR3.6 + 73.4 SF3.6 + 72.8 SP3.6 + 71.7 TF3.6
!
Subject to

!the following constraints
!
!CED (GJ)
1078 BC + 1004 MR3.9 + 999 SF3.9 + 1019 SP3.9 + 977 TF3.9 + 1039 MR3.6 + 1041 SF3.6 + 1035 SP3.6 + 1021 TF3.6 <= 1078
!
!Water Use (kL)
3103 BC + 2501 MR3.9 + 2471 SF3.9 + 2518 SP3.9 + 3093 TF3.9 + 2459 MR3.6 + 2469 SF3.6 + 2459 SP3.6 + 3072 TF3.6 <= 3103
!
!Waste impact (Tonne)
80.8 BC + 75.4 MR3.9 + 75.1 SF3.9 + 75.4 SP3.9 + 82.2 TF3.9 + 75.4 MR3.6 + 75.2 SF3.6 + 75.3 SP3.6 + 82.2 TF3.6 <= 82.2
!
!Life Cycle Costs
208656 BC + 209127 MR3.9 + 206758 SF3.9 + 206659 SP3.9 + 208360 TF3.9 + 209576 MR3.6 + 208494 SF3.6 + 207513 SP3.6 + 208987 TF3.6 <= 209576
!
!Choose at least one
BC + MR3.9 + SF3.9 + SP3.9 + TF3.9 + MR3.6 + SF3.6 + SP3.6 + TF3.6 >=1
!
END
!
!All binary integers
INT BC
INT MR3.9
INT SF3.9
INT SP3.9
INT TF3.9
INT MR3.6
INT SF3.6
INT SP3.6
INT TF3.6

Optimisation Model Results:

```
LP OPTIMUM FOUND AT STEP        2
OBJECTIVE VALUE =    68.1999969

NEW INTEGER SOLUTION OF     68.1999969     AT BRANCH      0 PIVOT        2
RE-INSTALLING BEST SOLUTION...

       OBJECTIVE FUNCTION VALUE

       1)       68.20000

  VARIABLE        VALUE          REDUCED COST
        BC         0.000000         80.800003
     MR3.9         0.000000         70.300003
     SF3.9         0.000000         69.900002
     SP3.9         0.000000         71.699997
     TF3.9         1.000000         68.199997
     MR3.6         0.000000         72.800003
     SF3.6         0.000000         73.400002
     SP3.6         0.000000         72.800003
     TF3.6         0.000000         71.699997


      ROW   SLACK OR SURPLUS     DUAL PRICES
       2)       101.000000         0.000000
       3)        10.000000         0.000000
       4)         0.000003         0.000000
       5)      1216.000000         0.000000
       6)         0.000000         0.000000

NO. ITERATIONS=       2
BRANCHES=     0 DETERM.=   1.000E    0
```

Appendix 8.F: Houses with roof designs: all the affects at least as good as "average" value

Minimise GHG Emission

Optimisation Model:

!Let BC be Base case
!Let MR3.9 be Metal roof house 3.9 star design

```
!Let MR3.6 be Metal roof house 3.6 star design
!Let SF3.9 be Skillion flat roof house 3.9 star design
!Let SF3.6 be Skillion flat roof house 3.6 star design
!Let SP3.9 be Skillion pitch roof house 3.9 star design
!Let SP3.6 be Skillion pitch roof house 3.6 star design
!Let TF3.9 be Tiled flat roof house 3.9 star design
!Let TF3.6 be Tiled flat roof house 3.6 star design
!
!Objective: Minimize Life cycle GHG (tonne CO2)
!
Min 80.8 BC + 70.3 MR3.9 + 69.9 SF3.9 + 71.7 SP3.9 + 68.2 TF3.9 + 72.8 MR3.6 + 73.4 SF3.6 + 72.8 SP3.6 + 71.7 TF3.6
!
Subject to
!the following constraints
!
!CED (GJ)
1078 BC + 1004 MR3.9 + 999 SF3.9 + 1019 SP3.9 + 977 TF3.9 + 1039 MR3.6 + 1041 SF3.6 + 1035 SP3.6 + 1021 TF3.6 <=
1023.6
!
!Water Use (kL)
3103 BC + 2501 MR3.9 + 2471 SF3.9 + 2518 SP3.9 + 3093 TF3.9 + 2459 MR3.6 + 2469 SF3.6 + 2459 SP3.6 + 3072 TF3.6 <=
2682
!
!Waste impact (Tonne)
80.8 BC + 75.4 MR3.9 + 75.1 SF3.9 + 75.4 SP3.9 + 82.2 TF3.9 + 75.4 MR3.6 + 75.2 SF3.6 + 75.3 SP3.6 + 82.2 TF3.6 <= 77.4
!
!Life Cycle Costs
208656 BC +  209127 MR3.9 + 206758 SF3.9 + 206659 SP3.9 + 208360 TF3.9 + 209576 MR3.6 + 208494 SF3.6 + 207513
SP3.6 + 208987 TF3.6 <= 208237
!
!Choose at least one
BC + MR3.9 + SF3.9 + SP3.9 + TF3.9 + MR3.6 + SF3.6 + SP3.6 + TF3.6 >=1
!
END
!
!All binary integers
INT BC
INT MR3.9
INT SF3.9
INT SP3.9
INT TF3.9
INT MR3.6
INT SF3.6
INT SP3.6
INT TF3.6
```

Optimisation Model Results:

```
LP OPTIMUM FOUND AT STEP        4
OBJECTIVE VALUE =    69.3492966

NEW INTEGER SOLUTION OF     69.9000015      AT BRANCH        0 PIVOT          4
RE-INSTALLING BEST SOLUTION...

       OBJECTIVE FUNCTION VALUE

       1)      69.90000

 VARIABLE        VALUE          REDUCED COST
       BC         0.000000         80.800003
    MR3.9         0.000000         70.300003
    SF3.9         1.000000         69.900002
    SP3.9         0.000000         71.699997
    TF3.9         0.000000         68.199997
    MR3.6         0.000000         72.800003
    SF3.6         0.000000         73.400002
    SP3.6         0.000000         72.800003
    TF3.6         0.000000         71.699997


      ROW   SLACK OR SURPLUS     DUAL PRICES
       2)        24.600000         0.000000
       3)       211.000000         0.000000
       4)         2.300002         0.000000
       5)      1479.000000         0.000000
       6)         0.000000         0.000000

NO. ITERATIONS=        4
BRANCHES=      0 DETERM.=    1.000E    0
```

Appendix 8.G: Houses with floor designs: all the affects at least as good as "highest" value

Minimise GHG Emission

Optimisation Model:

```
!Let BC be Base case
!Let CFH be Carpeted floor house
!Let CTH be Ceramic tiled floor house
!Let TFH be Timber floor house
!Let MFH be Mixed floor house
!
!Objective: Minimize Total Life Cycle GHG (Tonne)
!
Min 76.2 BC + 76.5 CFH + 67.1 CTH + 68.8 TFH + 65.1 MFH
!
Subject to
!the following constraints
!
!CED (GJ)
1078 BC + 1092 CFH + 975 CTH + 996 TFH + 940 MFH <= 1092
!
!Water Use (kL)
3103 BC + 3281 CFH + 3114 CTH + 3113 TFH + 3091 MFH <= 3281
!
!Waste impact (Tonne)
80.8 BC + 80.3 CFH + 80.8 CTH + 80.5 TFH + 81.1 MFH <= 81.1
!
!Life Cycle Costs
208656 BC +  201711 CFH + 202024 CTH + 207696 TFH + 201601 MFH <= 208656
!
!Choose at least one
BC + CFH + CTH + TFH + MFH >= 1
!
END
!
!All binary integers
INT BC
INT CFH
INT CTH
INT TFH
INT MFH
```

Optimisation Model Results:

```
LP OPTIMUM FOUND AT STEP        2
OBJECTIVE VALUE =    65.0999985

NEW INTEGER SOLUTION OF     65.0999985      AT BRANCH       0 PIVOT        2
RE-INSTALLING BEST SOLUTION...

       OBJECTIVE FUNCTION VALUE

       1)       65.10000

 VARIABLE          VALUE          REDUCED COST
       BC           0.000000         76.199997
      CFH           0.000000         76.500000
      CTH           0.000000         67.099998
      TFH           0.000000         68.800003
      MFH           1.000000         65.099998

      ROW    SLACK OR SURPLUS     DUAL PRICES
       2)         152.000000         0.000000
       3)         190.000000         0.000000
       4)           0.000002         0.000000
       5)        7055.000000         0.000000
       6)           0.000000         0.000000

NO. ITERATIONS=       2
BRANCHES=      0 DETERM.=    1.000E    0
```

Appendix 8.H: Houses with floor designs: all the affects at least as good as "average" value

Minimise GHG Emission

Optimisation Model:

!Let BC be Base case
!Let CFH be Carpeted floor house
!Let CTH be Ceramic tiled floor house
!Let TFH be Timber floor house
!Let MFH be Mixed floor house
!
!Objective: Minimize Total Life Cycle GHG (Tonne)
!
Min 76.2 BC + 76.5 CFH + 67.1 CTH + 68.8 TFH + 65.1 MFH
!
Subject to
!the following constraints
!
!CED (GJ)
1078 BC + 1092 CFH + 975 CTH + 996 TFH + 940 MFH <= 1016
!
!Water Use (kL)
3103 BC + 3281 CFH + 3114 CTH + 3113 TFH + 3091 MFH <= 3141
!
!Waste impact (Tonne)
80.8 BC + 80.3 CFH + 80.8 CTH + 80.5 TFH + 81.1 MFH <= 81.7
!
!Life Cycle Costs
208656 BC + 201711 CFH + 202024 CTH + 207696 TFH + 201601 MFH <= 204338
!
!Choose at least one
BC + CFH + CTH + TFH + MFH >= 1
!
END
!
!All binary integers
INT BC
INT CFH
INT CTH
INT TFH
INT MFH

Optimisation Model Results:

```
LP OPTIMUM FOUND AT STEP        2
OBJECTIVE VALUE =    65.0999985

NEW INTEGER SOLUTION OF     65.0999985      AT BRANCH       0 PIVOT         2
RE-INSTALLING BEST SOLUTION...

       OBJECTIVE FUNCTION VALUE

       1)       65.10000

 VARIABLE           VALUE          REDUCED COST
       BC          0.000000          76.199997
      CFH          0.000000          76.500000
      CTH          0.000000          67.099998
      TFH          0.000000          68.800003
      MFH          1.000000          65.099998


      ROW   SLACK OR SURPLUS      DUAL PRICES
       2)         76.000000          0.000000
       3)         50.000000          0.000000
       4)          0.600002          0.000000
       5)       2737.000000          0.000000
       6)          0.000000          0.000000

NO. ITERATIONS=        2
BRANCHES=      0 DETERM.=   1.000E     0
```

Appendix 8.I: Normalise weighted-sum results –wall design: all the effects at least as good as “highest”

<u>Minimise life cycle (.10 GHG + .10 CED + .80 COSTS): all the effects at least as good as the average</u>

<u>Optimisation Model:</u>

```
!Let BH3.9 be Brick House 3.9 star design
!Let CH3.9 be Concrete House 3.9 star design
!Let FC3.9 be FC sheet House 3.9 star design
!Let PL3.9 be Pine log House 3.9 star design
!Let WB3.9 be Weatherboard House 3.9 star design
!Let BH3.8 be Brick House 3.8 star design
!Let CH3.8 be Concrete House 3.8 star design
!Let FC3.8 be FC sheet House 3.8 star design
!Let PL3.8 be Pine log House 3.8 star design
!Let WB3.8 be Weatherboard House 3.8 star design
!Let BH3.7 be Brick House 3.7 star design
!Let CH3.7 be Concrete House 3.7 star design
!Let FC3.7 be FC sheet House 3.7 star design
!Let PL3.7 be Pine log House 3.7 star design
!Let WB3.7 be Weatherboard House 3.7 star design
!Let CH3.6 be Concrete House 3.6 star design
!Let FC3.6 be FC sheet House 3.6 star design
!Let WB3.6 be Weatherboard House 3.8 star design
!Let BC be Base case
!
!Objective: Minimize Total Life Cycle (.10 GHG + .10 CED + .80 COSTS)
!
Min 1.062 BH3.9 + 1.055 CH3.9 + 1.026 FC3.9 + 1.140 PL3.9 + 1.032 WB3.9 + 1.052 BH3.8 + 1.054 CH3.8 + 1.026 FC3.8 +
1.136 PL3.8 + 1.033 WB3.8 + 1.054 BH3.7 + 1.056 CH3.7 + 1.019 FC3.7 + 1.137 PL3.7 + 1.026 WB3.7 + 1.058 CH3.6 + 1.022
FC3.6 + 1.027 WB3.6 + 1.024 BC
!
Subject to
!the following constraints
!
!GHG (Tonne)
1.16 BH3.9 + 1.15 CH3.9 + 1.10 FC3.9 + 1.00 PL3.9 + 1.07 WB3.9 + 1.18 BH3.8 + 1.16 CH3.8 + 1.11 FC3.8 + 1.01 PL3.8 + 1.09
WB3.8 + 1.20 BH3.7 + 1.18 CH3.7 + 1.15 FC3.7 + 1.03 PL3.7 + 1.12 WB3.7 + 1.19 CH3.6 + 1.16 FC3.6 + 1.13 WB3.6 + 1.17 BC <=
1.20
!
!CED (GJ)
1.06 BH3.9 + 1.03 CH3.9 + 1.04 FC3.9 + 1.00 PL3.9 + 1.03 WB3.9 + 1.06 BH3.8 + 1.04 CH3.8 + 1.04 FC3.8 + 1.01 PL3.8 + 1.03
WB3.8 + 1.07 BH3.7+ 1.06 CH3.7 + 1.04 FC3.7 + 1.02 PL3.7 + 1.03 WB3.7 + 1.06 CH3.6 + 1.05 FC3.6 + 1.05 WB3.6 + 1.06 BC
<= 1.07
!
!Water Use (kL)
1.01 BH3.9 + 1.01 CH3.9 + 1.01 FC3.9 + 1 PL3.9 + 1 WB3.9 + 1.01 BH3.8 + 1.01 CH3.8 + 1.01 FC3.8 + 1 PL3.8 + 1 WB3.8 + 1.01
BH3.7 + 1.01 CH3.7 + 1.01 FC3.7 + 1 PL3.7 + 1 WB3.7 + 1.01 CH3.6 + 1.01 FC3.6+ 1 WB3.6 + 1.01 BC <= 1.01
!
!Waste impact (Tonne)
1.24 BH3.9 + 1.13 CH3.9 + 1.04 FC3.9 + 1.06 PL3.9 + 1.01 WB3.9 + 1.23 BH3.8 + 1.13 CH3.8 + 1.05 FC3.8 + 1.06 PL3.8 + 1.01
WB3.8 + 1.23 BH3.7 + 1.12 CH3.7 + 1.03 FC3.7 + 1.05 PL3.7 + 1.00 WB3.7 + 1.12 CH3.6 + 1.03 FC3.6 + 1 WB3.6 + 1.03 BC <=
1.24
!
!Life Cycle Costs
1.05 BH3.9 + 1.05 CH3.9 + 1.02 FC3.9 + 1.18 PL3.9 + 1.03 WB3.9 + 1.04 BH3.8 + 1.04 CH3.8 + 1.01 FC3.8 + 1.17 PL3.8 + 1.03
WB3.8 + 1.03 BH3.7 + 1.04 CH3.7 + 1 FC3.7 + 1.16 PL3.7 + 1.01 WB3.7 + 1.04 CH3.6 + 1 FC3.6 + 1.01 WB3.6 + 1 BC <= 1.18
!
!Choose at least one
BH3.9 + CH3.9 + FC3.9 + PL3.9 + WB3.9 + BH3.8 + CH3.8 + FC3.8 + PL3.8 + WB3.8 + BH3.7 + CH3.7 + FC3.7 + PL3.7 +
WB3.7 + CH3.6 + FC3.6 + WB3.6 + BC >= 1
!
END
!
!All binary integers
INT BH3.9
INT CH3.9
INT FC3.9
INT PL3.9
```

INT WB3.9
INT BH3.8
INT CH3.8
INT FC3.8
INT PL3.8
INT WB3.8
INT BH3.7
INT CH3.7
INT FC3.7
INT PL3.7
INT WB3.7
INT CH3.6
INT FC3.6
INT WB3.6
INT BC

Optimisation Model Results:

```
LP OPTIMUM FOUND AT STEP       2
OBJECTIVE VALUE =    1.01900005

FIX ALL VARS.(    18)  WITH RC >  0.000000E+00

NEW INTEGER SOLUTION OF     1.01900005     AT BRANCH       0 PIVOT        2
BOUND ON OPTIMUM:   1.019000
ENUMERATION COMPLETE. BRANCHES=      0 PIVOTS=        2

LAST INTEGER SOLUTION IS THE BEST FOUND
RE-INSTALLING BEST SOLUTION...

       OBJECTIVE FUNCTION VALUE

       1)      1.019000

  VARIABLE        VALUE          REDUCED COST
     BH3.9         0.000000          1.062000
     CH3.9         0.000000          1.055000
     FC3.9         0.000000          1.026000
     PL3.9         0.000000          1.140000
     WB3.9         0.000000          1.032000
     BH3.8         0.000000          1.052000
     CH3.8         0.000000          1.054000
     FC3.8         0.000000          1.026000
     PL3.8         0.000000          1.136000
     WB3.8         0.000000          1.033000
     BH3.7         0.000000          1.054000
     CH3.7         0.000000          1.056000
     FC3.7         1.000000          1.019000
     PL3.7         0.000000          1.137000
     WB3.7         0.000000          1.026000
     CH3.6         0.000000          1.058000
     FC3.6         0.000000          1.022000
     WB3.6         0.000000          1.027000
        BC         0.000000          1.024000


      ROW   SLACK OR SURPLUS     DUAL PRICES
       2)         0.050000          0.000000
       3)         0.030000          0.000000
       4)         0.000000          0.000000
       5)         0.210000          0.000000
       6)         0.180000          0.000000
       7)         0.000000          0.000000

NO. ITERATIONS=       2
BRANCHES=    0 DETERM.=   1.000E    0
```

Appendix 8.J: Normalise weighted-sum results –wall design: all the effects at least as good as "average"

<u>Minimise life cycle (.20 GHG + .20 CED + .20 water + .20 waste + .20 costs): all the effects at least as good as the average</u>

<u>Optimisation Model:</u>

!Let BH3.9 be Brick House 3.9 star design
!Let CH3.9 be Concrete House 3.9 star design
!Let FC3.9 be FC sheet House 3.9 star design
!Let PL3.9 be Pine log House 3.9 star design
!Let WB3.9 be Weatherboard House 3.9 star design
!Let BH3.8 be Brick House 3.8 star design
!Let CH3.8 be Concrete House 3.8 star design
!Let FC3.8 be FC sheet House 3.8 star design
!Let PL3.8 be Pine log House 3.8 star design
!Let WB3.8 be Weatherboard House 3.8 star design
!Let BH3.7 be Brick House 3.7 star design
!Let CH3.7 be Concrete House 3.7 star design
!Let FC3.7 be FC sheet House 3.7 star design
!Let PL3.7 be Pine log House 3.7 star design
!Let WB3.7 be Weatherboard House 3.7 star design
!Let CH3.6 be Concrete House 3.6 star design
!Let FC3.6 be FC sheet House 3.6 star design
!Let WB3.6 be Weatherboard House 3.8 star design
!Let BC be Base case
!
!Objective: Minimize Total Life Cycle COST and IMPACT
!
Min 1.102 BH3.9 + 1.074 CH3.9 + 1.042 FC3.9 + 1.046 PL3.9 + 1.028 WB3.9 + 1.103 BH3.8 + 1.077 CH3.8 + 1.045 FC3.8 + 1.049 PL3.8 + 1.031 WB3.8 + 1.109 BH3.7 + 1.083 CH3.7 + 1.047 FC3.7 + 1.054 PL3.7 + 1.033 WB3.7 + 1.087 CH3.6 + 1.052 FC3.6 + 1.039 WB3.6 + 1.056 BC
!
Subject to
!the following constraints
!
!GHG (Tonne)
1.16 BH3.9 + 1.15 CH3.9 + 1.10 FC3.9 + 1.00 PL3.9 + 1.07 WB3.9 + 1.18 BH3.8 + 1.16 CH3.8 + 1.11 FC3.8 + 1.01 PL3.8 + 1.09 WB3.8 + 1.20 BH3.7 + 1.18 CH3.7 + 1.15 FC3.7 + 1.03 PL3.7 + 1.12 WB3.7 + 1.19 CH3.6 + 1.16 FC3.6 + 1.13 WB3.6 + 1.17 BC <= 1.12
!
!CED (GJ)
1.06 BH3.9 + 1.03 CH3.9 + 1.04 FC3.9 + 1.00 PL3.9 + 1.03 WB3.9 + 1.06 BH3.8 + 1.04 CH3.8 + 1.04 FC3.8 + 1.01 PL3.8 + 1.03 WB3.8 + 1.07 BH3.7+ 1.06 CH3.7 + 1.04 FC3.7 + 1.02 PL3.7 + 1.03 WB3.7 + 1.06 CH3.6 + 1.05 FC3.6 + 1.05 WB3.6 + 1.06 BC <= 1.04
!
!Water Use (kL)
1.01 BH3.9 + 1.01 CH3.9 + 1.01 FC3.9 + 1 PL3.9 + 1 WB3.9 + 1.01 BH3.8 + 1.01 CH3.8 + 1.01 FC3.8 + 1 PL3.8 + 1 WB3.8 + 1.01 BH3.7 + 1.01 CH3.7 + 1.01 FC3.7 + 1 PL3.7 + 1 WB3.7 + 1.01 CH3.6 + 1.01 FC3.6+ 1 WB3.6 + 1.01 BC <= 1.01
!
!Waste impact (Tonne)
1.24 BH3.9 + 1.13 CH3.9 + 1.04 FC3.9 + 1.06 PL3.9 + 1.01 WB3.9 + 1.23 BH3.8 + 1.13 CH3.8 + 1.05 FC3.8 + 1.06 PL3.8 + 1.01 WB3.8 + 1.23 BH3.7 + 1.12 CH3.7 + 1.03 FC3.7 + 1.05 PL3.7 + 1.00 WB3.7 + 1.12 CH3.6 + 1.03 FC3.6 + 1 WB3.6 + 1.03 BC <= 1.09
!
!Life Cycle Costs
1.05 BH3.9 + 1.05 CH3.9 + 1.02 FC3.9 + 1.18 PL3.9 + 1.03 WB3.9 + 1.04 BH3.8 + 1.04 CH3.8 + 1.01 FC3.8 + 1.17 PL3.8 + 1.03 WB3.8 + 1.03 BH3.7 + 1.04 CH3.7 + 1 FC3.7 + 1.16 PL3.7 + 1.01 WB3.7 + 1.04 CH3.6 + 1 FC3.6 + 1.01 WB3.6 + 1 BC <= 1.05
!
!Choose at least one
BH3.9 + CH3.9 + FC3.9 + PL3.9 + WB3.9 + BH3.8 + CH3.8 + FC3.8 + PL3.8 + WB3.8 + BH3.7 + CH3.7 + FC3.7 + PL3.7 + WB3.7 + CH3.6 + FC3.6 + WB3.6 + BC >= 1
!
END
!
!All binary integers
INT BH3.9
INT CH3.9
INT FC3.9
INT PL3.9

INT WB3.9
INT BH3.8
INT CH3.8
INT FC3.8
INT PL3.8
INT WB3.8
INT BH3.7
INT CH3.7
INT FC3.7
INT PL3.7
INT WB3.7
INT CH3.6
INT FC3.6
INT WB3.6
INT BC

Optimisation Model Results:

```
LP OPTIMUM FOUND AT STEP      2
OBJECTIVE VALUE =   1.02800000

FIX ALL VARS.(   18)  WITH RC >  0.000000E+00

NEW INTEGER SOLUTION OF    1.02800000     AT BRANCH      0 PIVOT       2
BOUND ON OPTIMUM:  1.028000
ENUMERATION COMPLETE. BRANCHES=     0 PIVOTS=       2

LAST INTEGER SOLUTION IS THE BEST FOUND
RE-INSTALLING BEST SOLUTION...

       OBJECTIVE FUNCTION VALUE

       1)      1.028000

  VARIABLE        VALUE          REDUCED COST
     BH3.9         0.000000          1.102000
     CH3.9         0.000000          1.074000
     FC3.9         0.000000          1.042000
     PL3.9         0.000000          1.046000
     WB3.9         1.000000          1.028000
     BH3.8         0.000000          1.103000
     CH3.8         0.000000          1.077000
     FC3.8         0.000000          1.045000
     PL3.8         0.000000          1.049000
     WB3.8         0.000000          1.031000
     BH3.7         0.000000          1.109000
     CH3.7         0.000000          1.083000
     FC3.7         0.000000          1.047000
     PL3.7         0.000000          1.054000
     WB3.7         0.000000          1.033000
     CH3.6         0.000000          1.087000
     FC3.6         0.000000          1.052000
     WB3.6         0.000000          1.039000
        BC         0.000000          1.056000


      ROW   SLACK OR SURPLUS     DUAL PRICES
       2)         0.050000          0.000000
       3)         0.010000          0.000000
       4)         0.010000          0.000000
       5)         0.080000          0.000000
       6)         0.020000          0.000000
       7)         0.000000          0.000000

NO. ITERATIONS=       2
BRANCHES=    0 DETERM.=   1.000E    0
```

Appendix 8.K: Normalise weighted-sum results –roof design: all the effects at least as good as "average"

<u>Minimise life cycle (.10 GHG + .10 CED + .80 COSTS): all the effects at least as good as the average</u>

Optimisation Model:

```
!Let MR3.9 be Metal roof house 3.9 star design
!Let MR3.6 be Metal roof house 3.6 star design
!Let SF3.9 be Skillion flat roof house 3.9 star design
!Let SF3.6 be Skillion flat roof house 3.6 star design
!Let SP3.9 be Skillion pitch roof house 3.9 star design
!Let SP3.6 be Skillion pitch roof house 3.6 star design
!Let TF3.9 be Tiled flat roof house 3.9 star design
!Let TF3.6 be Tiled flat roof house 3.6 star design
!
!Objective: Minimize Total Life Cycle (.10 GHG + .10 CED + .80 COSTS)
!
Min 1.015 MR3.9 + 1.005 SF3.9 + 1.009 SP3.9 + 1.007 TF3.9 + 1.024 MR3.6 + 1.021 SF3.6 + 1.016 SP3.6 + 1.019 TF3.6
!
Subject to
!the following constraints
!
!GHG (Tonne)
1.031 MR3.9 + 1.024 SF3.9 + 1.051 SP3.9 + 1.00 TF3.9 + 1.067 MR3.6 + 1.076 SF3.6 + 1.066 SP3.6 + 1.050 TF3.6 <= 1.09
!
!CED (GJ)
1.027 MR3.9 + 1.022 SF3.9 + 1.042 SP3.9 + 1.00 TF3.9 + 1.062 MR3.6 + 1.065 SF3.6 + 1.059 SP3.6 + 1.045 TF3.6 <= 1.05
!
!Water Use (kL)
1.017 MR3.9 + 1.005 SF3.9 + 1.024 SP3.9 + 1.258 TF3.9 + 1.00 MR3.6 + 1.004 SF3.6 + 1 SP3.6 + 1.25 TF3.6 <= 1.05
!
!Waste impact (Tonne)
1.004 MR3.9 + 1 SF3.9 + 1.003 SP3.9 + 1.095 TF3.9 + 1.003 MR3.6 + 1.001 SF3.6 + 1.002 SP3.6 + 1.094 TF3.6 <= 1.03
!
!Life Cycle Costs
1.012 MR3.9 + 1.0 SF3.9 + 1.0 SP3.9 + 1.008 TF3.9 + 1.014 MR3.6 + 1.009 SF3.6 + 1.004 SP3.6 + 1.011 TF3.6 <= 1.01
!
!Choose at least one
MR3.9 + SF3.9 + SP3.9 + TF3.9 + MR3.6 + SF3.6 + SP3.6 + TF3.6 >= 1
!
END
!
!All binary integers
INT MR3.9
INT SF3.9
INT SP3.9
INT TF3.9
INT MR3.6
INT SF3.6
INT SP3.6
INT TF3.6
```

Optimisation Model Results:

```
LP OPTIMUM FOUND AT STEP      2
OBJECTIVE VALUE =    1.00500000


NEW INTEGER SOLUTION OF     1.00500000     AT BRANCH      0 PIVOT       2
RE-INSTALLING BEST SOLUTION...

       OBJECTIVE FUNCTION VALUE

       1)      1.005000

 VARIABLE        VALUE          REDUCED COST
    MR3.9         0.000000          1.015000
    SF3.9         1.000000          1.005000
    SP3.9         0.000000          1.009000
    TF3.9         0.000000          1.007000
    MR3.6         0.000000          1.024000
    SF3.6         0.000000          1.021000
    SP3.6         0.000000          1.016000
    TF3.6         0.000000          1.019000


      ROW   SLACK OR SURPLUS     DUAL PRICES
       2)         0.066000          0.000000
       3)         0.028000          0.000000
       4)         0.045000          0.000000
       5)         0.030000          0.000000
       6)         0.010000          0.000000
       7)         0.000000          0.000000

NO. ITERATIONS=       2
BRANCHES=    0 DETERM.=   1.000E    0
```

Appendix 8L: Normalise weighted-sum results –floor design: all the effects at least as good as "average"

Minimise life cycle (.10 GHG + .10 CED + .80 COSTS): all the effects at least as good as the average

Optimisation Model:

!Let CFH be Carpeted floor house
!Let CTH be Ceramic tiled floor house
!Let TFH be Timber floor house
!Let MFH be Mixed floor house
!
!Objective: Minimize Total Life Cycle (.25 GHG + .25 CED + .50 COSTS)
!
Min 1.034 CFH + 1.009 CTH + 1.036 TFH + 1 MFH
!
Subject to
!the following constraints
!
!GHG (Tonne)
1.175 CFH + 1.031 CTH + 1.056 TFH + 1.0 MFH <= 1.08
!
!CED (GJ)
1.162 CFH + 1.037 CTH + 1.060 TFH + 1.00 MFH <= 1.05
!
!Water Use (kL)
1.061 CFH + 1.007 CTH + 1.007 TFH + 1 MFH <= 1.04
!
!Waste impact (Tonne)
1.0 CFH + 1.006 CTH + 1.001 TFH + 1.009 MFH <= 1.03

```
!
!Life Cycle Costs
1.001CFH + 1.002 CTH + 1.03 TFH + 1 MFH <= 1.06
!
!Choose at least one
CFH + CTH + TFH + MFH >= 1
!
END
!
!All binary integers
INT CFH
INT CTH
INT TFH
INT MFH
```

Optimisation Model Results:

```
LP OPTIMUM FOUND AT STEP        2
OBJECTIVE VALUE =    1.00000000

NEW INTEGER SOLUTION OF     1.00000000      AT BRANCH       0 PIVOT        2
RE-INSTALLING BEST SOLUTION...

       OBJECTIVE FUNCTION VALUE

       1)       1.000000

  VARIABLE        VALUE          REDUCED COST
       CFH         0.000000          1.034000
       CTH         0.000000          1.009000
       TFH         0.000000          1.036000
       MFH         1.000000          1.000000

       ROW   SLACK OR SURPLUS     DUAL PRICES
        2)         0.080000          0.000000
        3)         0.050000          0.000000
        4)         0.040000          0.000000
        5)         0.021000          0.000000
        6)         0.060000          0.000000
        7)         0.000000          0.000000

NO. ITERATIONS=       2
BRANCHES=     0 DETERM.=   1.000E    0
```

Appendix 8.M: floor, wall and roof assemblage's arrangements of optimum house

Optimal house OP1: TFH/WB3.9/TF3.9

<table>
<tr><td rowspan="2">Floor-TFH</td><td>Ground floor
(Dining and Living)</td><td>Ground floor
(wet areas & Kitchen)</td><td>Upper floor (bed room, veranda and corridor)</td><td>upper floor
(wet areas)</td></tr>
<tr><td>T&G timber(19mm)
Ply wood (12mm)
Floor bearers, joist
Concrete slab: 2400kg/m3</td><td>Ceramic tiles
Ply wood (12mm)
Floor bearers, joist
Concrete slab: 2400kg/m3</td><td>T&G timber board pine (19mm)
Ply wood (12mm)
Glass fibre batt: R1.5
Floor bearers, joist
Plaster board</td><td>Ceramic tiles (8mm)
Ply wood (12mm)
Glass fibre batt: R1.5
Floor bearers, joist
Plaster board</td></tr>
<tr><td>Wall-WB3.9</td><td colspan="4">Weatherboard 12mm
Building paper
Air gap (40mm)
Glass fibre batt R1.5
Softwood plates, studs, noggins
Glass fibre batt R1.5
Particleboard 33mm
Plasterboard</td></tr>
<tr><td rowspan="2">Roof-TF3.9</td><td colspan="2">Rooftop assemblage</td><td>Upper floor ceiling</td><td>Ground floor ceiling</td></tr>
<tr><td colspan="2">Roof Tile (20mm)
Air gap (40mm)
Sarking
Glass fibre batt: R1.5
Rafters, battens
Polystyrene: R2.5</td><td>Polystyrene extruded: R3
Softwood ceiling joists
Glass fibre batt: R1
Plasterboard</td><td>Timber/Ceramic tiles
Plywood
Ceiling joists
Glass fibre batt: R1.5
Plasterboard</td></tr>
</table>

Optimal house OP2: MFH/WB3.9/SF3.9

<table>
<tr><td rowspan="2">Floor-MFH</td><td>Ground floor
(Dining and Living)</td><td>Ground floor
(wet areas & Kitchen)</td><td>upper floor (bed room, veranda and corridor)</td><td>upper floor
(wet areas)</td></tr>
<tr><td>Ceramic tiles
Ply wood (12mm)
Floor bearers, joist
Concrete slab: 2400kg/m3</td><td>Ceramic tiles
Ply wood (12mm)
Floor bearers, joist
Concrete slab: 2400kg/m3</td><td>T&G timber board pine (19mm)
Ply wood (12mm)
Glass fibre batt: R1.5
Floor bearers, joist
Plaster board</td><td>Ceramic tiles (8mm)
Ply wood (12mm)
Floor bearers, joist
Plaster board</td></tr>
<tr><td>Wall-WB3.9</td><td colspan="4">Weatherboard 12mm
Building paper
Air gap (40mm)
Glass fibre batt R1.5
Softwood plates, studs, noggins
Glass fibre batt R1.5
Particleboard 33mm
Plasterboard</td></tr>
<tr><td rowspan="2">Roof-SF3.9</td><td colspan="2">Rooftop assemblage</td><td colspan="2">Ceiling</td></tr>
<tr><td colspan="2">Steel metal roof (2mm)
Air gap (40mm)
Sarking (reflective foil laminates)
Cellulose fibre (loose fill): R3</td><td colspan="2">Polystyrene extruded: R3.5
Softwood ceiling joists
Glass fibre batt: R1.5
Plasterboard</td></tr>
</table>

<u>Optimal house OP3: MFH/FC3.9/SF3.9</u>

<table>
<tr><td rowspan="2">Floor-MFH</td><td>Ground floor
(Dining and Living)</td><td>Ground floor
(wet areas & Kitchen)</td><td colspan="2">upper floor (bed room, veranda and corridor)</td><td>upper floor
(wet areas)</td></tr>
<tr><td>T&G timber board (19mm)
Ply wood (12mm)
Floor bearers, joist
Concrete slab: 2400kg/m3</td><td>Ceramic tiles
Ply wood (12mm)
Floor bearers, joist
Concrete slab: 2400kg/m3</td><td colspan="2">T&G timber board pine (19mm)
Ply wood (12mm)
Glass fibre batt: R1.5
Floor bearers, joist
Plaster board</td><td>Ceramic tiles (8mm)
Ply wood (12mm)
Glass fibre batt: R1.5
Floor bearers, joist
Plaster board</td></tr>
<tr><td>Wall-FC3.9</td><td colspan="5">FC Sheet
Building paper (vapour barrier)
Air gap (40mm)
Glass fibre batt: R1.5
Softwood plates, studs, noggins
Glass fibre batt: R1.5
Particleboard: 33mm
Plasterboard</td></tr>
<tr><td rowspan="2">Roof-SF3.9</td><td colspan="3">Rooftop assemblage</td><td colspan="2">Ceiling</td></tr>
<tr><td colspan="3">Steel metal roof (2mm)
Air gap (40mm)
Sarking (reflective foil laminates)
Cellulose fibre (loose fill): R3</td><td colspan="2">Polystyrene extruded: R3.5
Softwood ceiling joists
Glass fibre batt: R1.5
Plasterboard</td></tr>
</table>

Appendix 8.N: Normalise weighted-sum results –optimum and case study house: all the effects at least as good as "average"

1. Minimise life cycle (.20 GHG + .20 CED + .20 water + .20 waste +.20 costs): all the effects at least as good as the average

Optimisation Model:

```
!Let OP1 be optimum house number 1
!Let OP1 be optimum house number 2
!Let OP1 be optimum house number 3
!Let BC be Base case house
!
!Objective: Minimize Total Life Cycle (.2 GHG + .2 CED + .2 WATER + .2 WASTE + .2 COST)
!
Min 1.12 OP1 + 1 OP2 + 1.02 OP3 + 1.14 BC
!
Subject to
!the following constraints
!
!GHG (Tonne)
1.01 OP1 + 1 OP2 + 1.03 OP3 + 1.21 BC <= 1.062
!
!CED (GJ)
1.03 OP1 + 1.0 OP2 + 1.02 OP3 + 1.12 BC <= 1.042
!
!Water Use (kL)
1.43 OP1 + 1.0 OP2 + 1.01 OP3 + 1.25 BC <= 1.173
!
!Waste impact (Tonne)
1.08 OP1 + 1.0 OP2 + 1.02 OP3 + 1.10 BC <= 1.051
!
!Life Cycle Costs
1.03 OP1 + 1.01 OP2 + 1 OP3 + 1.01 BC <= 1.013
!
!Choose at least one
BC + OP1 + OP2 + OP3 >= 1
!
END
!
!All binary integers
INT OP1
INT OP2
INT OP3
INT BC
```

Optimisation Model Results:

```
LP OPTIMUM FOUND AT STEP        2
OBJECTIVE VALUE =    1.00000000

NEW INTEGER SOLUTION OF     1.00000000      AT BRANCH      0 PIVOT        2
RE-INSTALLING BEST SOLUTION...

       OBJECTIVE FUNCTION VALUE

       1)      1.000000

  VARIABLE        VALUE          REDUCED COST
       OP1         0.000000          1.120000
       OP2         1.000000          1.000000
       OP3         0.000000          1.020000
        BC         0.000000          1.140000

       ROW   SLACK OR SURPLUS     DUAL PRICES
        2)         0.062000          0.000000
        3)         0.042000          0.000000
        4)         0.173000          0.000000
        5)         0.051000          0.000000
        6)         0.003000          0.000000
        7)         0.000000          0.000000

NO. ITERATIONS=        2
BRANCHES=     0 DETERM.=   1.000E    0
```

2. Minimise life cycle (.33 GHG + .33 CED + .34 COSTS): all the effects at least as good as the average

Optimisation Model:

```
!Let OP1 be optimum house number 1
!Let OP1 be optimum house number 2
!Let OP1 be optimum house number 3
!Let BC be Base case house
!
!Objective: Minimize Total Life Cycle (.2 GHG + .2 CED + .2 WATER + .2 WASTE + .2 COST)
!
Min 1.025 OP1 + 1.003 OP2 + 1.015 OP3 + 1.110 BC
!
Subject to
!the following constraints
!
!GHG (Tonne)
1.01 OP1 + 1 OP2 + 1.03 OP3 + 1.21 BC <= 1.062
!
!CED (GJ)
1.03 OP1 + 1.0 OP2 + 1.02 OP3 + 1.12 BC <= 1.042
!
!Water Use (kL)
1.43 OP1 + 1.0 OP2 + 1.01 OP3 + 1.25 BC <= 1.173
!
!Waste impact (Tonne)
1.08 OP1 + 1.0 OP2 + 1.02 OP3 + 1.10 BC <= 1.051
!
!Life Cycle Costs
1.03 OP1 + 1.01 OP2 + 1 OP3 + 1.01 BC <= 1.013
!
!Choose at least one
BC + OP1 + OP2 + OP3 >= 1
!
END
!
!All binary integers
INT OP1
INT OP2
INT OP3
INT BC
```

Optimisation Model Results:

```
LP OPTIMUM FOUND AT STEP        2
OBJECTIVE VALUE =    1.00300002

NEW INTEGER SOLUTION OF     1.00300002      AT BRANCH       0 PIVOT        2
RE-INSTALLING BEST SOLUTION...

       OBJECTIVE FUNCTION VALUE

       1)        1.003000

 VARIABLE        VALUE          REDUCED COST
      OP1         0.000000          1.025000
      OP2         1.000000          1.003000
      OP3         0.000000          1.015000
       BC         0.000000          1.110000


      ROW   SLACK OR SURPLUS     DUAL PRICES
       2)         0.062000          0.000000
       3)         0.042000          0.000000
       4)         0.173000          0.000000
       5)         0.051000          0.000000
       6)         0.003000          0.000000
       7)         0.000000          0.000000

NO. ITERATIONS=        2
BRANCHES=     0 DETERM.=   1.000E    0
```

3. Minimise life cycle (.13 GHG + .13 CED + .74 COSTS): all the effects at least as good as the average

Optimisation Model:

```
!Let OP1 be optimum house number 1
!Let OP1 be optimum house number 2
!Let OP1 be optimum house number 3
!Let BC be Base case house
!
!Objective: Minimize Total Life Cycle (.2 GHG + .2 CED + .2 WATER + .2 WASTE + .2 COST)
!
Min 1.031 OP1 + 1.006 OP2 + 1.006 OP3 + 1.048 BC
!
Subject to
!the following constraints
!
!GHG (Tonne)
1.01 OP1 + 1 OP2 + 1.03 OP3 + 1.21 BC <= 1.062
!
!CED (GJ)
1.03 OP1 + 1.0 OP2 + 1.02 OP3 + 1.12 BC <= 1.042
!
!Water Use (kL)
1.43 OP1 + 1.0 OP2 + 1.01 OP3 + 1.25 BC <= 1.173
!
!Waste impact (Tonne)
1.08 OP1 + 1.0 OP2 + 1.02 OP3 + 1.10 BC <= 1.051
!
!Life Cycle Costs
1.03 OP1 + 1.01 OP2 + 1 OP3 + 1.01 BC <= 1.013
!
!Choose at least one
BC + OP1 + OP2 + OP3 >= 1
!
END
!
!All binary integers
INT OP1
INT OP2
INT OP3
INT BC
```

Optimisation Model Results:

```
LP OPTIMUM FOUND AT STEP       4
OBJECTIVE VALUE =    1.00600004

NEW INTEGER SOLUTION OF     1.00600004     AT BRANCH      0 PIVOT       4
RE-INSTALLING BEST SOLUTION...

       OBJECTIVE FUNCTION VALUE

       1)      1.006000

 VARIABLE        VALUE          REDUCED COST
      OP1        0.000000          1.031000
      OP2        0.000000          1.006000
      OP3        1.000000          1.006000
       BC        0.000000          1.048000

      ROW   SLACK OR SURPLUS     DUAL PRICES
       2)        0.032000          0.000000
       3)        0.022000          0.000000
       4)        0.163000          0.000000
       5)        0.031000          0.000000
       6)        0.013000          0.000000
       7)        0.000000          0.000000

NO. ITERATIONS=       4
BRANCHES=     0 DETERM.=   1.000E    0
```

Appendix 8.O: Normalise weighted-sum results –optimum and case study house: all the effects at least as good as "highest"

1. Minimise life cycle (.20 GHG + .20 CED + .20 Water + .20 Waste +.20 Costs): all the effects at least as good as the average

Optimisation Model:

```
!Let OP1 be optimum house number 1
!Let OP1 be optimum house number 2
!Let OP1 be optimum house number 3
!Let BC be Base case house
!
!Objective: Minimize Total Life Cycle (.2 GHG + .2 CED + .2 WATER + .2 WASTE + .2 COST)
!
Min 1.12 OP1 + 1 OP2 + 1.02 OP3 + 1.14 BC
!
Subject to
!the following constraints
!
!GHG (Tonne)
1.01 OP1 + 1 OP2 + 1.03 OP3 + 1.21 BC <= 1.21
!
!CED (GJ)
1.03 OP1 + 1.0 OP2 + 1.02 OP3 + 1.12 BC <= 1.12
!
!Water Use (kL)
1.43 OP1 + 1.0 OP2 + 1.01 OP3 + 1.25 BC <= 1.125
!
!Waste impact (Tonne)
1.08 OP1 + 1.0 OP2 + 1.02 OP3 + 1.10 BC <= 1.10
!
!Life Cycle Costs
1.03 OP1 + 1.01 OP2 + 1 OP3 + 1.01 BC <= 1.03
!
!Choose at least one
BC + OP1 + OP2 + OP3 >= 1
!
END
!
!All binary integers
INT OP1
INT OP2
INT OP3
INT BC
```

Optimisation Model Results:

```
LP OPTIMUM FOUND AT STEP       2
OBJECTIVE VALUE =    1.00000000

NEW INTEGER SOLUTION OF     1.00000000      AT BRANCH       0 PIVOT        2
RE-INSTALLING BEST SOLUTION...

       OBJECTIVE FUNCTION VALUE

       1)       1.000000

  VARIABLE         VALUE          REDUCED COST
       OP1        0.000000          1.120000
       OP2        1.000000          1.000000
       OP3        0.000000          1.020000
        BC        0.000000          1.140000


       ROW   SLACK OR SURPLUS     DUAL PRICES
        2)        0.210000          0.000000
        3)        0.120000          0.000000
        4)        0.125000          0.000000
        5)        0.100000          0.000000
        6)        0.020000          0.000000
        7)        0.000000          0.000000

NO. ITERATIONS=       2
BRANCHES=     0 DETERM.=   1.000E    0
```

2. Minimise life cycle (.33 GHG + .33 CED + .34 COSTS): all the effects at least as good as the highest

Optimisation Model:

!Let OP1 be optimum house number 1
!Let OP1 be optimum house number 2
!Let OP1 be optimum house number 3
!Let BC be Base case house
!
!Objective: Minimize Total Life Cycle (.2 GHG + .2 CED + .2 WATER + .2 WASTE + .2 COST)
!
Min 1.025 OP1 + 1.003 OP2 + 1.015 OP3 + 1.110 BC
!
Subject to
!the following constraints
!
!GHG (Tonne)
1.01 OP1 + 1 OP2 + 1.03 OP3 + 1.21 BC <= 1.21
!
!CED (GJ)
1.03 OP1 + 1.0 OP2 + 1.02 OP3 + 1.12 BC <= 1.12
!
!Water Use (kL)
1.43 OP1 + 1.0 OP2 + 1.01 OP3 + 1.25 BC <= 1.125
!
!Waste impact (Tonne)
1.08 OP1 + 1.0 OP2 + 1.02 OP3 + 1.10 BC <= 1.10
!
!Life Cycle Costs
1.03 OP1 + 1.01 OP2 + 1 OP3 + 1.01 BC <= 1.03
!
!Choose at least one
BC + OP1 + OP2 + OP3 >= 1
!
END
!
!All binary integers
INT OP1
INT OP2
INT OP3
INT BC

Optimisation Model Results:

```
LP OPTIMUM FOUND AT STEP      2
OBJECTIVE VALUE =    1.00300002


NEW INTEGER SOLUTION OF    1.00300002     AT BRANCH      0 PIVOT       2
RE-INSTALLING BEST SOLUTION...

       OBJECTIVE FUNCTION VALUE

       1)       1.003000

 VARIABLE        VALUE          REDUCED COST
      OP1        0.000000          1.025000
      OP2        1.000000          1.003000
      OP3        0.000000          1.015000
       BC        0.000000          1.110000


      ROW   SLACK OR SURPLUS     DUAL PRICES
       2)        0.210000          0.000000
       3)        0.120000          0.000000
       4)        0.125000          0.000000
       5)        0.100000          0.000000
       6)        0.020000          0.000000
       7)        0.000000          0.000000

NO. ITERATIONS=       2
BRANCHES=      0 DETERM.=   1.000E    0
```

3. Minimise life cycle (.13 GHG + .13 CED + .74 COSTS): all the effects at least as good as the highest

Optimisation Model:

```
!Let OP1 be optimum house number 1
!Let OP1 be optimum house number 2
!Let OP1 be optimum house number 3
!Let BC be Base case house
!
!Objective: Minimize Total Life Cycle (.13 GHG + .13 CED + .74 COST)
!
Min 1.031 OP1 + 1.006 OP2 + 1.006 OP3 + 1.048 BC
!
Subject to
!the following constraints
!
!GHG (Tonne)
1.01 OP1 + 1 OP2 + 1.03 OP3 + 1.21 BC <= 1.21
!
!CED (GJ)
1.03 OP1 + 1.0 OP2 + 1.02 OP3 + 1.12 BC <= 1.12
!
!Water Use (kL)
1.43 OP1 + 1.0 OP2 + 1.01 OP3 + 1.25 BC <= 1.125
!
!Waste impact (Tonne)
1.08 OP1 + 1.0 OP2 + 1.02 OP3 + 1.10 BC <= 1.10
!
!Life Cycle Costs
1.03 OP1 + 1.01 OP2 + 1 OP3 + 1.01 BC <= 1.03
!
!Choose at least one
BC + OP1 + OP2 + OP3 >= 1
!
END
!
!All binary integers
INT OP1
INT OP2
INT OP3
INT BC
```

Optimisation Model Results:

```
 LP OPTIMUM FOUND AT STEP        2
 OBJECTIVE VALUE =    1.00600004


 NEW INTEGER SOLUTION OF     1.00600004      AT BRANCH       0 PIVOT        2
 RE-INSTALLING BEST SOLUTION...

        OBJECTIVE FUNCTION VALUE

        1)       1.006000

  VARIABLE         VALUE          REDUCED COST
       OP1         0.000000          1.031000
       OP2         0.000000          1.006000
       OP3         1.000000          1.006000
        BC         0.000000          1.048000


       ROW   SLACK OR SURPLUS     DUAL PRICES
        2)         0.180000          0.000000
        3)         0.100000          0.000000
        4)         0.115000          0.000000
        5)         0.080000          0.000000
        6)         0.030000          0.000000
        7)         0.000000          0.000000

 NO. ITERATIONS=       2
 BRANCHES=      0 DETERM.=   1.000E     0
```